

FIGURE. | *Woolly mammoth skeleton, composite of 185 bones trawled from the seabed, Mammuthus primigenius. Photo: Hans Wildschut.*

Fossil bones from the North Sea: Radiocarbon dating

U vindt een Nederlandse samenvatting aan het eind van de tekst.

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Abstract | The North Sea is a unique heritage site yielding a large amount of palaeontological and archaeological data. Here we report and discuss ^{14}C dates of fossil bone samples from the North Sea. About 2/3 of these are Pleistocene in age; many dates are from extinct species, in particular the woolly mammoth. About 1/3 of the samples date to the Holocene. The latter include human bones, mostly (sub)recent but also including an unique Mesolithic dataset.

Introduction

During the last ice age, large volumes of water were stored in the continental ice caps. As a consequence, sea

levels were roughly 100 m lower than today. At that time, the southern North Sea was a diverse and rich landscape inhabited by a rich fauna; it was



in fact part of the Mammoth Steppe (e.g. Mol *et al.*, 2008; Kuitens, 2020). Also humans lived in the area, in particular during the Mesolithic as evidenced by bones and artifacts (Roebroeks, 2014). Recent investigations have increased our insights into geographical aspects of this now submerged landscape (e.g. Gaffney *et al.*, 2007). This is discussed in other contributions of this volume.

Nevertheless, still many unanswered questions exist about the animals and people who occupied the area despite the large quantities of fossil bones and occasional artifacts extracted from the seabed. The main reason is that most of the finds derive from unknown stratigraphical, geographical, and archaeological contexts (Peeters, 2011). The majority of finds has been brought up in fishing nets or came ashore in sand dredged from the seabed for the purpose of coastal reinforcement and land reclamation. Nonetheless, several zones in the southern North Sea, for instance the Bruine Bank (Brown Bank) and Eurogeul (Eurogully), are known as palaeontological and/or archaeological ‘hot spots’ which have been subject to targeted ‘fishing’ expeditions. A rare location where research of *in situ* contexts could be conducted is Rotterdam-Maasvlakte (2).

A crucial aspect concerning the fossil finds is the establishment of their age. Many samples have been submitted for ^{14}C dating during the last decades, resulting in an important and unique series of dates. In addition, analysis of the stable isotopes (^{13}C and ^{15}N) of the dated bone collagen has become an important dataset by itself. For the stable isotopes, we refer to the accompanying article in this volume. They are proxies that can be used for reconstruction of, and for information on (palaeo)climatological and environmental change. A prime example concerns dietary information of the Mesolithic hunter-gatherers of Doggerland; the stable isotope contents of their bones indicate that their major food resource must have been freshwater fish (van der Plicht *et al.*, 2016).

This contribution presents an overview of fossil bones analysed for their natural isotopes. It comprises more than 200 animal bone dates and more than 100 human bone dates, all with a North Sea context. It provides a catalogue of samples measured for their isotopes, in particular ^{14}C . The vast majority of the measurements were done in Groningen. These were supplemented by a limited set of ^{14}C dates available from other laboratories. These isotopic data provide a major contribution towards an integrated understanding of the North Sea in the past. Detailed palaeontological, archaeological and geophysical interpretations of data shown in the catalogue are discussed in other contributions of this volume.

Occasionally, questions have been raised about ^{14}C dating and interpretation of the results. This paper therefore starts with an up to date review of the method.

Radiocarbon dating

The Radiocarbon (^{14}C) dating method was developed during the years around 1950 (Taylor *et al.*, 1992). The method enables direct dating of organic remains back to about 50,000 years ago. Since that time, several “revolutions” have improved the method considerably. Among the most significant ones are the introduction of AMS in the 1980s, and calibration of the ^{14}C timescale.

AMS (Accelerator Mass Spectrometry) enables small (milligram size) sample analysis (Tuniz *et al.*, 1998). This is a factor of 1000 less than the original, so-called conventional method based on radiometry (Mook and Streurman, 1983). AMS therefore enables ^{14}C dating of precious fossils, such as archaic human bones and bone artifacts, as well as intrinsically small samples such as botanical remains (macrofossils and seeds) and foraminifera.

Calibration now enables absolute dating back to 50,000 years ago, i.e. the complete dating range. In turn, this spawned “revolutions” in the fields of application, among which archaeology, palaeontology and quaternary geology. Radiocarbon provides a “yardstick of time”, enabling the measurement of past time by scientific means, independent of associations and assumptions. This enables synchronisation and chronological comparison of different areas at excavation sites and also between sites and regions. This is essential for proper

interpretation of archaeological or stratigraphical layers and association with data obtained from other disciplines.

While the method is basically simple, it is complex in detail in matters concerning both fieldwork and technical laboratory aspects. Therefore, stringent quality control is necessary to build up reliable ^{14}C chronologies. This involves regular laboratory intercomparisons, duplicate measurements of samples, issues such as conventional versus AMS, sample selection, contamination, association, and others (summarized in van Strydonck *et al.*, 1999).

The element carbon consists of three naturally occurring isotopes: ^{12}C , ^{13}C and ^{14}C with abundances of ca. 98.9 %, 1.1 % and 10^{-10} %, respectively. The isotope ^{14}C (Radiocarbon) is continuously produced in the Earth’s atmosphere by cosmic radiation. Radiocarbon is radioactive and decays with a half-life of 5730 years. A stationary state of production, distribution between the main carbon reservoirs (atmosphere, ocean and biosphere) and decay results in a more or less constant ^{14}C concentration in atmospheric CO_2 and subsequently in the terrestrial biosphere. However this concentration (the above mentioned number 10^{-10} %) is not a true constant, there are (relatively small) variations which are discussed below. Upon death of an organism, the radioactive ^{14}C decays, and by measuring the amount of remaining ^{14}C in the sample its time of death can be derived. For accurate Radiocarbon dating, only the ^{14}C that was part of the organism when it died should be measured.

It is known for some time that the ^{14}C concentration of atmospheric CO_2 has not always been the same in the past. In tree rings, natural variations of the atmospheric $^{14}\text{CO}_2$ abundance were discovered on a time scale of one decade to a few centuries. These variations can be attributed to variations in solar activity, and changes of the geomagnetic field strength. They both modulate the cosmic ray flux near the Earth and thus the production of ^{14}C in the atmosphere. Because of these variations in the natural ^{14}C concentration, the ^{14}C



clock runs at a varying pace, different from real clocks: ^{14}C time is not equivalent to calendar time, and their relationship is not linear.

Another complication arises from mass dependent effects, affecting processes in nature and in the laboratory. This is known as “isotope fractionation”. For example, in biological pathways lighter isotopes are taken up preferentially, reducing the proportion of ^{14}C in a sample making it seem older.

These (and other) problems in establishing an accurate ^{14}C date are solved by the so-called “Radiocarbon convention”.

The “Radiocarbon convention” is a normalization. This formally comprises

1. The ^{14}C radioactivity is measured relative to that of a standard (Oxalic Acid with a radioactivity of 0.226 Bq/gC), representing modern natural Radiocarbon which relates to 1950 AD
2. From this measured radioactivity the “Radiocarbon age” is calculated using a half-life of 5568 years
3. Isotopic fractionation is corrected for by measuring the fractionation of the stable isotope ^{13}C of the dated sample to $\delta^{13}\text{C} = -25\text{‰}$ (see below)
4. The Radiocarbon age is expressed in the unit BP

The half-life value 5568 was used in the early days of ^{14}C dating and is not correct, the proper value was later established as the above mentioned 5730 ± 40 years. The original value however is still used in order not to cause confusion; the error that is introduced this way is corrected for later (by calibration).

Concerning the fractionation correction, there exists a numerical relation between that of ^{13}C and that of ^{14}C . Fractionation is expressed in δ -values which are explained in the methods paragraph below.

The defined conventional ^{14}C timescale is expressed in the unit BP. This originally meant “Before Present”. The expression “Present”, originally taken as 1950 AD, should not be taken literally because the relation between the ^{14}C timescale and the calendar timescale is complex. This relation is determined by calibration. It is also theoretically different from “BP” as used in other dating methods.

For technical details, we refer to Mook and van der Plicht (1999).

Thus, the ^{14}C timescale is defined and has to be calibrated to establish the relationship between ^{14}C time and historical time. Calibration involves measuring samples by both the ^{14}C method (reported in BP) and another method. Ideally this other method has to be independent from ^{14}C , yielding absolute dates (in AD/BC), and the samples have to be from the terrestrial (or atmospheric) reservoir. The paired dates (BP and AD/BC) then are used to construct a calibration curve, which gives the relationship between both timescales. For the dates calibrated using this curve, the effects of the chosen convention values for half-life and fractionation correction are then automatically taken into account.

In this article, we will express calendar ages in calBP. This is defined as calendar years with respect to 1950 AD (thus, calBP=1950-AD).

The most ideal samples for calibration are tree rings, because they can be dated absolutely by means of dendrochronology. The ^{14}C community has released special issues of the journal *Radiocarbon* with calibration curves based on a variety of records available. These issues are updated regularly. The main data are tree rings dated by both ^{14}C and dendrochronology. Beyond the available absolutely dated dendrochronological dataset, records from varves (laminated sediments containing botanical remains), plus corals, foraminifera and speleothems which are also dated by Uranium isotopes are used. The latter requires reservoir corrections (see below); the main varved record is from Lake Suigetsu (Japan) and is terrestrial (Bronk Ramsey *et al.*, 2012).

Using these datasets, the calibration curve named IntCal20 has been constructed, covering the complete ^{14}C date range (Reimer *et al.*, 2020). It is the presently recommended calibration curve and is shown in Figure 1 (in thousands of years, ka BP and ka calBP). The calibration dataset is plotted in red; for guidance, the dashed blue line represents BP=calBP, i.e. represents a natural ^{14}C level which would have been constant throughout the past millennia. The dashed green line at 13,910 calBP separates the dendrochronological part and the part derived from other records.

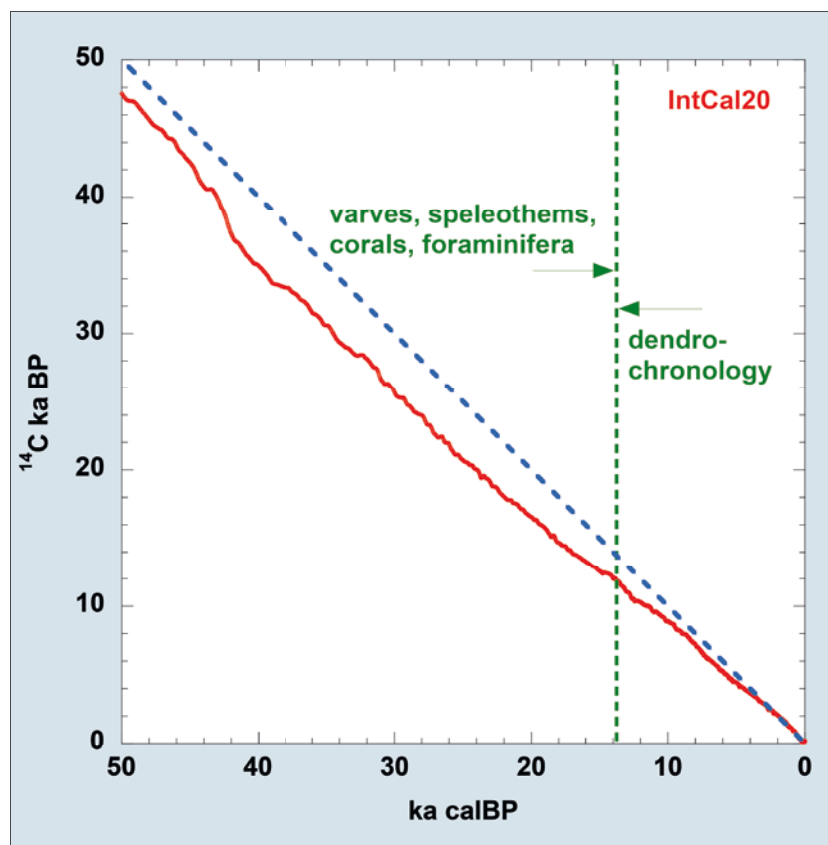


FIGURE 1. | The calibration curve IntCal20, to be used for transferring ^{14}C dates (vertical, BP) into calendar ages (horizontal, calBP = 1950-AD).



The calibration curve shows a wealth of information on past events.

On the scale shown in Figure 1, it shows a long term (millennia scale) trend caused by changes in the geomagnetic field strength. The field strength was lower in the Late Pleistocene, resulting in a larger ^{14}C production rate in the atmosphere. In turn this means ^{14}C dates become younger: 47,000 ^{14}C years ago (BP) corresponds to about 50,000 calendar years ago (calBP). On this long-term trend, modulations on century/decennium scale (known as “wiggles”) are present. They are barely or not visible in Figure 1, but can be observed by zooming in, in particular in the dendrochronological part of the curve. These are caused by fluctuations in solar activity, which also influence the ^{14}C production rate in the atmosphere. These data are instrumental for the study of past climate changes, like the Pleistocene/Holocene transition and the Younger Dryas cold episode, often discussed in relation to megafauna extinction. This is not further discussed here, but all interpretations depend on accurate dating.

The ^{14}C convention is defined for terrestrial material, which is in equilibrium with atmospheric CO_2 . Reservoirs like oceans, rivers and lakes contain dissolved CO_2 , which generally contains less ^{14}C than the atmosphere. This causes apparent ages for organisms acquiring their carbon from these reservoirs through the food chain: the so-called “reservoir effect”, which needs to be corrected for in order to obtain absolute dates.

The surface water of the oceans is characterised by rapid exchange of CO_2 (which includes $^{14}\text{CO}_2$) between the atmosphere and surface water. Exchange between surface water and deep water is very slow. The amount of deep water is considerably larger than that of surface water. Together with the slow exchange rate this results in a much lower ^{14}C activity in deep water than in surface water. Due to the welling up of deep water, the surface water contains about 5% less ^{14}C than expected. This corresponds to 400 ^{14}C years and is called the “marine reservoir effect” (Alves *et al.*, 2018); correction must be made for this effect by subtracting 400 years of the radiocarbon age, when reported in BP according to the convention. This correction applies to marine organisms, such as shell, fish, and corals. It also applies to mammals feeding on marine organisms such as whales, seals, dolphins, polar bears (Tauber, 1979) and includes humans like Inuit.

The above applies to the Holocene part of the ^{14}C dating range. For the older part, significant differences for the value 400 are observed, caused by rearrangements in the global carbon cycle. This depends on locality and time period. Thus, one cannot simply subtract 400 from these samples. For the oldest part of the ^{14}C range this is not very relevant, as the measurement uncertainties become comparable to or larger than the reservoir effect. Riverine reservoir effects are much larger than 400 years. For the North Sea this is relevant for samples from the drowned landscapes, such as Doggerland during the Mesolithic.

Note that “BP” does *not* include correction for reservoir effects; this easily leads to confusion, and published dates should be taken with care. In our date lists in this article reservoir effects are not subtracted. When samples are subject to reservoir effects that is indicated in the tables.

Isotope methods

For accurate ^{14}C dating, only the ^{14}C that was part of the organism when it died should be measured. Therefore, the first task in the laboratory is to remove any foreign carbon that entered the sample since that time. Such contamination comes principally from the burial environment. This is done by a mixture of physical and chemical means, using pre-treatment protocols. These procedures also isolate a purified chemical fraction of a sample – for example, collagen from bone, which is the most abundant protein in mammals. Bone is the vast majority of dated material presented in this article.

Collagen can be chemically isolated from the sample, generally by following an improved version of the original method known as the Longin method. In brief, the sample is first entirely released from bioapatite and contaminants such as humic acids. Subsequent heating at 90°C causes gelatinization of the

collagen (Mook & Streurman, 1983). For a complete description of sample pre-treatment aspects, we refer to Dee *et al.* (2020).

After drying, the crystalline collagen is combusted to produce CO_2 . This CO_2 gas contains the ^{14}C from the sample; dating is the measurement of this amount of ^{14}C .

For the conventional method, the ^{14}C radioactivity in the CO_2 is measured by radiometry. This ^{14}C radioactivity is extremely low. Therefore, special counters in a low-background setup are required, designed to shield the natural radioactivity. This method requires typically a litre of CO_2 gas, or a gram of carbon, or grams of sample material. The conventional, radiometric method was developed around 1950. In Groningen it was used between 1952 and 2011. For a complete description of the conventional method we refer to Mook & Streurman (1983).

AMS is a form of mass spectrometry, which means measuring the ^{14}C content directly instead of those ^{14}C atoms which decay by radioactivity. Mass spectrometry is much more efficient than radiometry, which enables a very significant reduction (by a factor of 1000) in sample size to typically 1 milligram of Carbon. The AMS technique was developed in the 1980s (Tuniz *et al.*, 1998).

For Radiocarbon, the natural concentration is so low that mass spectrometry at high voltages of about 250 kV or higher (i.e. a small particle accelerator) is required.

For AMS, the principles of the chemical/physical sample pre-treatment are the same as for the conventional method. But for AMS, one extra step is needed: the CO_2 gas needs to be reduced into graphite. The graphite is pressed into targets, mounted in a sample carousel before it is loaded into the ion source of the machine. Both ^{14}C measuring methods (radiometry and mass spectrometry) yield numbers in BP which have the same meaning.

Stable isotope concentrations are measured by mass spectrometry, based on molecular gases. The stable Carbon isotope (^{13}C) content of the sample is measured in CO_2 by IRMS



(Isotope Ratio Mass Spectrometry) upon combustion of the pre-treated ^{14}C sample material (such as collagen, prepared from fossil bone). Thus, the same CO_2 is used for both isotope measurements, ^{13}C and ^{14}C dating – either by AMS or by the conventional method.

For the Nitrogen isotope ^{15}N , also IRMS is used. In this case, N_2 gas is used prepared from the same collagen sample.

The stable isotopic content of the samples is expressed in delta (δ) values, which are defined as the deviation (expressed in permil) of the rare to abundant isotope ratio from that of a reference material:

$$\delta^{13}\text{C} = \left[\frac{(^{13}\text{R}_{\text{sample}}/^{13}\text{R}_{\text{reference}})}{(^{13}\text{R}/^{12}\text{C})} - 1 \right] (\times 1000\text{‰})$$

and

$$\delta^{15}\text{N} = \left[\frac{(^{15}\text{R}_{\text{sample}}/^{15}\text{R}_{\text{reference}})}{(^{15}\text{N}/^{14}\text{N})} - 1 \right] (\times 1000\text{‰})$$

The absolute isotope contents of the reference materials have been measured very accurately. For carbon, the reference material is belemnite carbonate (V-PDB); for nitrogen, the reference is ambient air (Mook, 2006).

The general research question for natural isotope analysis of North Sea fossil bones has been and still is ^{14}C dating, which is discussed here. The stable isotope values $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of the same bones dated by ^{14}C provide

additional information on paleo-environmental conditions, the diet of organisms and (when relevant) ^{14}C reservoir effects. The stable isotope results are discussed in depth in the accompanying paper in this volume.

Bone quality aspects

Bone collagen is sensitive to degradation. The most common indicators for collagen integrity are the carbon and nitrogen extraction yields of the collagen, denoted as %C and %N, respectively. These numbers are provided by the mass spectrometer. Also, the atomic C/N ratio, $\text{C/N} = (\% \text{C}/\% \text{N}) \times (14/12)$ is a widely accepted quality parameter. Based on comparison with the chemical composition of collagen extracted from fresh bone using the same purification treatment, the carbon content of genuine collagen should be around 30–40 % and its nitrogen content around 11–16 % for reliable results. The C/N ratio for well-preserved bone collagen is 2.9–3.6.

The weight proportion of the extracted collagen in relation to the initial sample weight (% yield) is preferably minimally 0.5. For fresh bone, this number is about 20%. See van Klinken (1999) and references therein.

In terms of contamination, one can calculate how much contamination is needed to explain aberrant dates. It obviously depends on the age of the contaminant, which theoretically can be any age between modern and fossil. Let us assume here modern contamination, then with a contamination of 1% modern Carbon a sample of 50,000 BP will be measured as 35,000 BP.

For the conventional method, this means a 1% foreign Carbon for a 1-gram sample is 10 mg which is quite much. The same calculations apply to AMS but the samples are much smaller. Here, a contamination of 1% foreign Carbon for a 1 mg sample is only 10 μg ; therefore, AMS is much more sensitive for contamination.

In natural circumstances, contamination can be caused by processes such as degradation which may enable invasion of carbon containing matter from the environment. This is particularly the case for Pleistocene samples. We do not have an example where this is clearly shown, because of the lack of context for the North Sea samples. The key for successful dating is quality control, in particular the Carbon content of the collagen, later supplemented by Nitrogen content. Also, the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values must be in certain ranges. For example, a $\delta^{13}\text{C}$ value of say -25‰ for bone can be suspect, in particular when the C content is low; contamination with material having low $\delta^{13}\text{C}$ values, like soil components, is not unlikely in such cases.

The development of the measurement techniques for ^{14}C and the stable isotopes are closely intertwined. Historically, first ^{14}C was measured only by radiometry in the form of CO_2 . Soon the phenomenon of fractionation was discovered, making additional measurements of ^{13}C necessary. This was done on the same CO_2 gas prepared from the sample. So, except for measurements done in the early days, for all dates (including the ones discussed in this paper) both Carbon isotopes ^{14}C and ^{13}C are measured. The IRMS technique required about 1 millilitre of CO_2 , or 1 milligram of C for the measurement of $\delta^{13}\text{C}$.

It appeared that for fossil bones, the $\delta^{13}\text{C}$ value of the collagen showed information on the (palaeo)diet of the organism (van der Merwe & Vogel, 1978). This became supplemented by $\delta^{15}\text{N}$ analysis of the same bone collagen. The IRMS used had to be setup for either Carbon or Nitrogen. This required analysis of a second bone sample – a sample for both C isotopes, and one for ^{15}N .

With the introduction of AMS, the sample size for ^{14}C was reduced to that similar for ^{13}C and ^{15}N . This meant that instead of large combustion systems necessary for conventional dating, automated combustion systems (EA, Elemental Analyser) could be used pro-

ducing CO_2 and N_2 gas from samples. These are coupled to a mass spectrometer (EA-IRMS), yielding both stable isotope ratios $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. Part of the CO_2 gas is rerouted to a system producing graphite for separate ^{14}C measurement by AMS.

Also for AMS, originally ^{15}N analysis required a second run on the EA-IRMS which was either set for Carbon, or for Nitrogen. Today, more modern apparatus can combust one sample and yield $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in one run.

All of this explains the perhaps confusing fact that the tables with results of isotope measurements in almost all cases show the $\delta^{13}\text{C}$ value of the dated fossil bone, and in more limited cases also the $\delta^{15}\text{N}$ value.

The story above applies to the Groningen laboratory, with both a conventional setup (used until 2011) and an AMS facility (since 1994). Most results in the tables are from Groningen. In addition, a few dates from the North Sea are measured elsewhere. From these other laboratories, the $\delta^{13}\text{C}$ values are always measured (and used for fractionation correction of the ^{14}C dates) but not always reported and thus not known to us; the $\delta^{15}\text{N}$ values are not always measured and also not known to us.



When the conservation circumstances are excellent, like in the permafrost, the collagen is usually perfect for dating, allowing dating to very old ages (slightly over 50,000 BP). An outstanding example is the Arilakh mammoth (see Mol *et al.*, 2006).

Taking this issues into consideration, together with discussions concerning which samples should be used as blank (background) for the ¹⁴C method, we set the upper limit for bone dating at 45,000 BP. For a detailed discussion we refer to van der Plicht and Palstra (2016).

Results

The vast majority of data in this overview is obtained by the Groningen laboratory. In the past also other laboratories contributed to the North Sea dataset. The laboratories can be recognized by internationally assigned laboratory codes as follows (see also www.radiocarbon.org), which are used in the data tables:

AA	Tucson (Arizona, USA)	AMS
GrN	Groningen (Netherlands)	conventional (1952-2011)
GrA	Groningen (Netherlands)	AMS (1994-2017)
GrM	Groningen (Netherlands)	AMS (since 2017)
K	Copenhagen (Denmark)	conventional
KIA	Kiel (Germany)	AMS
M	Mannheim (Germany)	AMS
OxA	Oxford (UK)	AMS
UtC	Utrecht (Netherlands)	AMS

We note that some codes and/or laboratories are no longer in use or active today; these are GrN, GrA, K and UtC.

The main result of ¹⁴C measurement is, of course, the dating itself: a direct measurement of the age of the sample, which is otherwise difficult or impossible to establish. This is especially true for the North Sea finds because there is in general a lack of context like stratigraphy and/or associations.

The results are shown in Tables 1-3 and are discussed in the paragraphs below. Tables 1 and 2 show the results for the animal bones, sorted to ¹⁴C age. Table 1 shows the animal bone results for ages older than the Holocene era. These cover the Late Pleistocene back to 45,000 BP. Bone dates with ¹⁴C ages older than 45,000 BP are considered 'background' (van der Plicht & Palstra, 2016) and reported as such (>45,000). Some ages in this time range have been reported as finite (i.e. a ¹⁴C age with measurement error), we consider these also as minimum ages. A ¹⁴C age of 45,000 BP corresponds to ca. 46,800 calBP after calibration.

Laboratory code, locality, ¹⁴C age and its uncertainty, species and skeletal element are shown, as well as the C and N contents and stable isotope ratios $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of the collagen, when available. The ¹⁴C dates are calibrated using the IntCal20 curve (Reimer *et al.*, 2020) and are given as 2 σ ranges in calBP. The numbers are rounded to significance.

Some dates are reported with asymmetric uncertainties. The reason is that the decay process is not linear: the activity A (number of decays) is an exponential function of time t. The measurement uncertainty is σ , and the measured activity is given as $A \pm \sigma$ which is symmetric. But when we calculate the time(age), the age distribution is in theory not symmetric because of the non-linearity. When ages are not too old, this is not important because the effect is small and can be ignored. It becomes relevant for high ages, close to the dating limit, where the activities $A - \sigma$ and $A + \sigma$ result in ages $T - \sigma_1$ and $T + \sigma_2$ respectively, with σ_1 different from σ_2 . In Table 1 we show these in 2 separate columns. When dates become younger, the 2 sigmas become equal (within the rounding applied). For asymmetric cases, dates are reported as $\text{BP}(-\sigma_1, +\sigma_2)$; in symmetric cases, they become $\text{BP} \pm \sigma$.

For the oldest samples, the counting rate cannot be distinguished from the background. In such cases, the dating limit is determined to be when the

measured activity is 2 times its error (sigma). The age is then given as older than (>) BP (Olsson, 1989).

Table 2 shows the animal bone results, corresponding to the Holocene era. Also here laboratory code, locality, ¹⁴C age and its uncertainty, species and skeletal element are shown, as well as the C and N contents and stable isotope ratios $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, when available. The calibrated ¹⁴C dates are given as 2 σ range in calBP.

Table 3 is the human dataset from the North Sea, showing laboratory number, locality, skeletal element, Radiocarbon age (BP), its measurement error (1sigma), Carbon yield (C%), $\delta^{13}\text{C}$ (‰), Nitrogen yield (N%), $\delta^{15}\text{N}$ (‰) and atomic C/N ratio of the collagen. No calibrated results are shown (see discussion below).

The tables also include a parameter "quality" which we have defined as follows. Accepted dates (unconditionally) are indicated by "a". They all meet the aspects concerning C and N. The label "1" means that not all criteria are known. For example, for samples measured by other laboratories we only have the ¹⁴C dates and not the other data. Mostly, the $\delta^{13}\text{C}$ values are not published or otherwise available. The label "2" means that not all criteria are strictly met, but the outcomes are reasonable. For example, a C/N ratio of 2.8 is strictly taken not acceptable. But one has to take into account that the C% and N% measurements from which the C/N ratio is calculated are not very precise. There is no good reason for rejection.

The label "3" means that only the C isotopes are measured (¹⁴C and ¹³C). This is related to the historical developments of the Radiocarbon method. During the early decades of the method, the N isotope of collagen has not been measured. This applies to almost all conventional dates and the early AMS dates. The measurement of N isotopes gradually became standard since the 1990s.

A few measurements can not be acceptable based on the quality parameters, but are shown for completeness. They are indicated by r (rejected) in the last column.

In all cases, we have used 0.5% collagen yield of the bone material as acceptance threshold.



In Figure 2 we show an overview of all dated bones, sorted taxonomically. A grand total of 337 dates (including duplicates) is represented: 210 for animals (136 Pleistocene and 74 Holocene), and 127 for humans.

In Figure 2, the ^{14}C ages (BP) are given instead of calibrated dates (calBP) to avoid reservoir effect ambiguities and still existing uncertainties in the oldest part of the calibration curve.

For completeness, note that the marine species are subject to reservoir effects. This also applies to the great auk. For non-marine aquatic species (in terms of diet), an unknown reservoir effect applies. This is the case for the otter. Also, humans with a subsistence of freshwater fish have an unknown reservoir effect (see below). On the scale used in Figure 2, however the reservoir effect is not visible.

Discussion: Radiocarbon dates of the fauna

This paragraph discusses aspects concerning the ^{14}C dating. For a full interpretation in terms of palaeontology and palaeo-landscape issues we refer to the other chapters of this volume.

some general observations for the ^{14}C dates

The data tables and Figure 2 show that the majority of the dates (about 2/3) correspond to the Pleistocene. These are all animal samples, including true “old ^{14}C dates” and ages which are infinite on the ^{14}C time scale, i.e. unknown age but older than 45,000 BP (about 47,000 calBP). A second group correspond to the Mesolithic era, around 9000 BP. These concern both human and animal fossil bones, including artifacts made of bone. Most human samples are (much) younger than the Mesolithic era. It appears that the LGM (Last Glacial Maximum) around 20,000 BP (^{14}C) seems to be more or less devoid of fossils.

Terrestrial animals dated thus far are straight tusked elephant, woolly mammoth, cave lion, sabre-toothed cat, arctic fox, hyena, dog/wolf, bear, otter, wolverine, woolly rhinoceros, horse, roe deer, moose, red deer, giant deer, reindeer, wild boar, musk ox,

steppe bison, aurochs, caprinae, other bovids, hare, and beaver.

Marine animals are bowhead whale, orca, common rorqual, beluga whale, grey whale, grey seal, bearded seal, walrus, bottlenose dolphin, white beaked dolphin, porpoise and harp seal.

In addition, the dataset contains one bird species (great auk).

It is of interest here to note that Late Pleistocene and Early Holocene mammals from two different sites in the Netherlands show many similarities. The faunal composition of the on-shore dredged site De Grootte Wielen (near Den Bosch) and the Eurogeul (North Sea) is almost identical. The ^{14}C dates show that the mammoth fauna are more or less of the same age. The results from De Grootte Wielen – in particular for woolly mammoth (*Mammuthus primigenius*) and woolly rhinoceros (*Coelodonta antiquitatis*) – can be found in Mol *et al.* (2010).

However, aspects such as taphonomic processes, choices for sediment used for sand suppletion projects, mesh size of fishing nets, detection of finds by (often amateur) collectors, and the glamour of specific finds dramatically determine the type of North Sea finds that are finally submitted for radiocarbon dating. Hence, the composition of the current dataset is biased, which affects the representation of species and periods.

For instance, small, fragile fish and bird bones are just sporadically submitted for radiocarbon dating. First of all, classical, precise excavation and sieving methods cannot be applied within the North Sea area, limiting the recovery of smaller sized finds. Moreover, often the collagen of such remains does not preserve well enough for dating purposes. In contrast to smaller animals, many human remains have been submitted for radiocarbon dating. A large part of these remains is relatively young and was submitted to resolve forensic questions. Also, a remarkably large number of samples are human bones thought to be Neanderthal, based on the measure of fossilization. Apparently, the circumstances in the North Sea are such that degree of fossilization is not a good measure

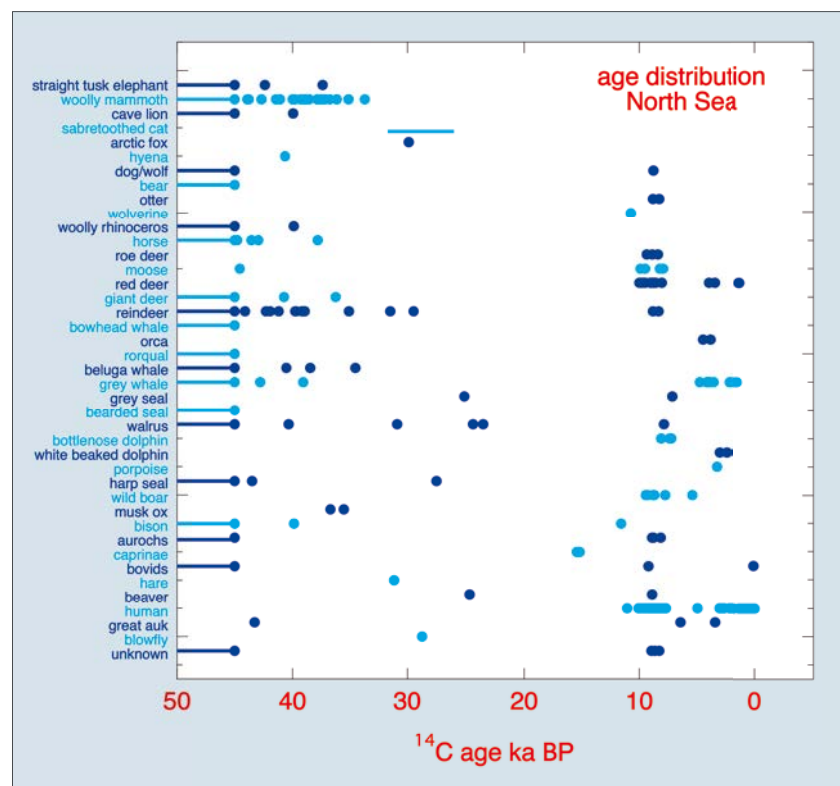


FIGURE 2. | Age distribution of all dated bones from the North Sea, organised by species or taxonomical family. A grand total of 337 dates is plotted. The horizontal lines at the left side of the figure correspond to ages larger than 45,000 BP. Dates reported as finite and older than 45,000 BP are truncated at 45,000 BP.



of age: thus far, all such bones turned out to be Mesolithic with only a few Late Palaeolithic exceptions. A particular important example is GrA-58271, a Late Glacial parietal bone, which is described in detail by Amkreutz *et al.* (2018). The human fossil samples are discussed below in a separate paragraph. Moreover, samples of cervids are represented in relatively high numbers in the radiocarbon dataset. Many of these are modified antlers. But also artifacts made of cervid bones and skeletal elements of bovids (e.g., a decorated, Late-Glacial bovid metatarsus (GrA-28364; also discussed in Amkreutz *et al.*, 2018)) and horses have been submitted for age determination.

Many finds come from a limited number of regions from the North Sea area, specifically locations that are frequently exploited by fishermen and that are suitable for sand extraction purposes. Indeed, more than a third of the samples come from the important fishing areas Eurogeul and the Bruine Bank. Also, a large part comes from the beaches of the Dutch province Zuid-Holland, in which many large sand suppletion projects took place in recent years.

Although this dataset reflects a biased composition of dwellers of the North Sea area in the past, it gives insight in aspects such as species present in different periods and chemical conservation of fossil remains, helps to solve geological puzzles of the North Sea bottom, and reveals some spectacular discoveries.

Apart from the Eurogeul, Bruine Bank, and Zuid-Holland, a major part of the samples comes from the province Zeeland, the Southern Bight of the North Sea and from the Wadden Sea. The samples from the other localities also vary in age from Pleistocene (or possibly older) to Holocene. The Bruine Bank and Eurogeul represent the highest number of different species (i.e., 24 and 23, respectively). Human remains are found in all localities, but the majority of *Homo sapiens* comes from Zuid-Holland and the Wadden Sea. Moreover, from all localities, samples from both marine and terrestrial species have been submitted. Remarkably, from the fifteen animal species that come from the Southern Bight, eleven belong to marine mammals.

context of the material

A difficult issue has always been the context of the finds from the North Sea. Only recently, a detailed stratigraphic framework has been made for the Eurogeul region (Hijma *et al.*, 2012) and for a small region offshore of the Maasvlakte 2 area (Busschers *et al.*, 2013). See also other contributions in this volume. The defined lithostratigraphic units show signs of repeated, severe reworking during various fluvial and/or marine depositional phases. Therefore, it is likely that none of the the Pleistocene North Sea assemblages, including the dated samples discussed in this paper, are pristine and free from mixing.

The geological framework presented by Hijma *et al.* (2012) even implies that all Late Pleistocene terrestrial mammals dating older than around 30,000 years must have been redeposited from their original location. However, overall, the skeletal remains from the North Sea are well preserved with just few signs of weathering and little or no rounding. Such taphonomic characteristics indicate that the skeletal material did not lie on the surface for long, nor was it transported over large distances. Therefore, many finds may derive from eroded, large lumps of such reworked (possibly frozen at that time) sediments (Kuitens *et al.*, 2013).

Besides the depositional history of the material, the way the fossils have been retrieved hampers assigning palaeontological and archaeological finds to a precise stratigraphic unit. That is, most fossils of large mammals are collected during fishing expeditions (Mol *et al.*, 2008). The rough location of the ship was reported along with many of the samples that were found in fishing nets. But, even the most detailed data available on location and depth of the nets are far from precise enough to link a find to a specific stratigraphical layer (Kuitens *et al.*, 2013).

However, combining the radiocarbon dates, ship's coordinates, geological information and knowledge of ecological preferences and restrictions of species,

a number of finds can be assigned to a specific lithological unit.

Below, selected results of the isotope date list for the North Sea fossil bones are discussed and highlighted here in more detail.

unique samples

Unique finds are first finds of certain species of the Mammoth steppe in the North Sea.

Among these is a first find of a hare (*Lepus* sp.) from the bottom of the North Sea, found at the Zandmotor. It is a mandible, ¹⁴C dated to 31,140 BP (GrA-54021). For more details, we refer to Mol & van der Plicht (2012a).

This result represents a first such old date for this species for the North Sea.

Also finds of bones from otters (*Lutra lutra*) yield the first dates for this species from the North Sea. They were recovered from the sand suppletion area for Maasvlakte 2 and from dredged sediments deposited on the beach of Hoek van Holland (Mol & van der Plicht, 2012b). Two specimens date to the Early Holocene: 8825 ± 45 BP (GrA-52432) and 8300 ± 40 BP (GrA-52433). This result provides a clear answer to the question whether these animals date to the mammoth fauna or not.

Another first age-establishment for a species in this particular area concerns an arctic fox (*Alopex lagopus*) from the Zandmotor, in the suppletted sand originating from the Eurogeul (Langeveld *et al.*, 2018). It is dated to 29,900 BP (GrA-69520). We note that an even younger arctic fox is known from De Groote Wielen near 's-Hertogenbosch, dating to 21,890 BP (GrA-35484).

A series of eleven fossil bones from the great auk (*Pinguinus impennis*) from the North Sea region was submitted for ¹⁴C dating. Unfortunately, only three samples appeared datable; the collagen yield of the others was too low. The collagen of the three analysed samples was of good quality (see C and N parameters, Table 1 and 2). Two samples from the Zandmotor dated Holocene, the youngest being 3505±45 BP (GrA-65546). One bone dated Pleistocene: 43,290 BP (GrA-64453).



The latter was found on the beach of Hoek van Holland.

The stable isotope ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) results of the three auk samples indicate a purely marine diet, as expected. That means that the dates need to be corrected for the reservoir effect. For the Holocene the correction is 400 years. The auks date 400 years too old on the ^{14}C timescale because of the reservoir effect. Thus, the youngest sample is 3105 ^{14}C years old, which calibrates into 1425–1300 BC.

A unique find of importance is a fossil bone (mandible with teeth) of a saber-toothed cat (*Homotherium latidens*) from the Brown Bank. A series of six samples was dated by AMS in Utrecht, resulting in a final date of ca. 28,000 BP (Reumer *et al.*, 2003). A few samples of mandible and tooth were dated with varying results in $\delta^{13}\text{C}$ and ^{14}C age. Hence, the six dates cover a significant range, which is indicated in Figure 2 as a horizontal bar because it concerns here only one specimen. These ^{14}C dates indicate that the species survived in the region well into the Late Pleistocene. However, no further quality parameters of the collagen are available.

relevant non-bone samples

There are a few samples with a North Sea context that were radiocarbon dated which are not bone or another skeletal part, but are relevant: wood, fly pupae, coprolites and plant remains. There is one wood sample with a context expected to be Mesolithic. It is a human worked wooden object of unknown function. The object is found in an area (De Stekels) from which worked antler/bone artifacts from the Mesolithic were recovered previously. The ^{14}C date, however, is modern; the measured activity is more than 100%, meaning it contains ^{14}C from the nuclear era corresponding to about 1960 AD (GrA-37939). The $\delta^{13}\text{C}$ value and Carbon content are within normal range. Perhaps the modern age is not surprising, and the presumed prehistoric association appeared not correct.

Another wood sample is found in an antler artifact, used as an axe. The axe dates 4030 ± 60 BP (GrA-20280). The wood dates 4180 ± 60 BP (GrA-20290), which is consistent within measurement uncertainty.

Fly pupae (*Protophormia terraenovae*) were found in a skull from a woolly mammoth dredged from the Eurogeul. They were dated by ^{14}C to 28,740 BP (GrA-50454; table 1) (van der Plicht *et al.*, 2012).

Like many other ^{14}C dates, this is younger than stratigraphic inferences for the Eurogeul. This is discussed in detail in other contributions of this volume. The importance of this fly pupae date, is that it is not obtained from fossil bone. Pleistocene bone collagen is often a subject of deliberations in terms of degradation and/or contamination. There is no reason at all to “suspect” the fly pupae date in this respect.

We note that there is one other fly pupae date known from De Groote Wielen near Den Bosch, the Netherlands, that was found in association with Late Pleistocene mammal bone. The date is $26,660 \pm 150$ BP (GrA-35816). This date shows the same general timerange as that of the Eurogeuly.

Over the last decade, several coprolites of hyena (*Crocota crocuta spelaea*) were found and dating has been attempted. However, because of the nature of the sample material this appeared problematic. One coprolite (found on the Brown Bank) contained a small bone and a small piece of wood. The latter dates to $18,310 \pm 150$ BP (GrA-59740). The bone appeared not datable. A coprolite found on Maasvlakte 2 (in sand originating from the Eurogeul) was dated as “organic matter”, yielding a ^{14}C age of $35,050 (+250, -240)$ BP (GrA-56323). The C content was low (4.9%), the $\delta^{13}\text{C}$ value -16.43‰ .

A recent find is a molar from a giant deer (*Megaloceros giganteus*). It was found on Zandmotor. Unfortunately, the collagen preservation of the molar appeared very poor. This sample is not included in the data table and figures. However, plant remains were preserved in the deep folds of the molar. This shows that the animal foraged in a steppe environment, eating Artemisia. For details we refer to van Geel *et al.* (2018). The plant remains are ^{14}C dated to $38,750 (+300, -290)$ BP (GrA-68256), corresponding to Greenland Interstadial GI-11.

anomalous ^{14}C dates

A striking example is a worked reindeer bone with cut marks displaying a human face. Archaeologically this is potentially a sensational sample, believed to date to the Mesolithic. But it dated to 1310 ± 60 BP (GrA-20291). Technically, this was a problematic sample because the bone had been treated with preservatives, and the material was very delicate. It was established by Radiocarbon that the artifact was not as old as was hoped; it is not related to ancient people living in what is today the North Sea area. A duplicate dating yields essentially the same date (GrA-22093, 1370 ± 40 BP). This pair of ^{14}C dates was the reason to change the identification from reindeer to red deer. Assuming the contamination was removed adequately, of course.

The preservative applied is known as Stelfon, which is of fossil origin (i.e. does not contain ^{14}C). So, in contrast to most collagen-containing contaminants, if contamination was left on the material after pre-treatment it measures older than its actual age.

Another anomalous sample is a “goatlike animal” (Caprinae) from the Brown Bank, which could not be further identified (JG-777). It dates to the Late Glacial: 15,190 BP (GrA-38211) which is impossible, or at least not very likely based on present palaeontological understanding. The sample was dated again, even in threefold, all with the same result (Table 1). There is no reason to doubt the dating; there are no signs of contamination, and the sample quality parameters are good. In theory the species identification could be problematic but that is not known. This sample is a mystery which still remains to be resolved.

issues near the ^{14}C limit

As expected, many of the (Late) Pleistocene fossils belonged to typical so-called mammoth steppe fauna. Moreover, a large number of Pleistocene fossils are from marine mammals. The set of ^{14}C dates for large marine mammals have raised questions, which still need to be resolved. That is, many whales date



between 35,000 and 45,000 BP and walrus between 25,000 and 30,000 BP. However, following Hijma *et al.* (2012), the marine fauna must be about 60,000–85,000 years old. Therefore, these ^{14}C dates have been criticised. Could contamination possibly cause anomalously young dates such that fossils of say 80,000 years old date 40,000 in the laboratory? This question has been raised earlier for the *Homotherium* (dating around 30,000 BP) and *Elephas antiquus* (37,440 BP, GrA-25815). These samples should perhaps be redated with more advanced techniques (Devièse *et al.*, 2018) for confirmation.

The above was a motivation to study in depth some technical issues concerning ^{14}C dating of Pleistocene (i.e. “old”) samples. This concerns laboratory inter-comparisons, backgrounds, contamination and pre-treatment. A series of mammoth bones from the North Sea has been investigated for this purpose. This “test series” resulted in valid dates which are shown in Tables 3 and 4 and concerns GrA-56655, 56656, 55658, 56660, 56661, 56662, 56664, 56674, 56675 and 56676.

Incidentally, of our test series GrA-56660 (a mammoth humerus from the Eurogeul) showed bite marks of Hyena. Hence, the ^{14}C date provides a date for this species, i.e. *cf. Crocuta crocuta spelaea*, as well.

Radiocarbon laboratories regularly organize exchange of samples varying in age and material to compare dating protocols. The latest intercomparison program is known as SIRI (Sixth International Radiocarbon Intercomparison), see www.radiocarbon.org.

The sample dated as GrA-56658 is already in use for the purpose and is now known as sample B for SIRI. The other North Sea bones are also shipped to the Glasgow laboratory (the coordinator of the comparison efforts) for possible future use.

Glue, and also other solutions, is often used for conservation and restauration purposes for fossils. However, glue contains collagen which is also the extracted datable fraction. Such contamination is not uncommon but “dangerous” for dating: when glue is not properly removed from the sample, that contamination is the obvious cause for the young date. This is clearly illustrated by the following example. A submitted small sample of a mammoth tooth from the North Sea yielded a very unlikely young date of 9,005 BP (GrA-50857). Upon close inspection of the whole tooth it became clear the material was heavily treated with glue as a preservative. Indeed, further test measurements using material from the inner part of the tooth and applying special chemical cleaning techniques yielded much older ^{14}C dates. Among these, the oldest date is 21,650 BP (GrA-57902) which still would be the youngest ^{14}C -dated mammoth of the Netherlands, but considering the nature of the sample, the sample was judged not-datable by ^{14}C . The results for GrA-50857 and GrA-57902 are rejected and not shown in the tables.

Another rejected “Holocene mammoth” (dated at 3,400 BP) is GrA-10928. The collagen extracted was of very low quality and quantity (C% = 4.5%). The chemical residue fraction is also dated, yielding $11,450 \pm 190$ BP (GrA-10929). This could theoretically be the true age of the mammoth, but it cannot be established with certainty.

Some samples are just lightly touched by glue which is supposedly efficiently removed, in particular with an extra chemical cleaning known as “soxhlet” (Dee *et al.*, 2020). Such contamination was applied to a series of samples from 6 miles east off the coast Great Yarmouth: GrA-39962, 39964, 39965, 39966, and 39121. Indeed, the resulting collagen parameters are well in their acceptable ranges, and the dates appear reasonable.

Also a bone sample from the Westerschelde (GrA-40013) was treated slightly with glue and we applied the soxhlet extraction here as well. The sample is dated to 42,400 BP. It is from an *Elephas antiquus* so the result has to be considered with care. There is no objective reason for rejection of the measurement, but also here confirmation would be a good thing. It is not the first finite ^{14}C age

for this species from the North Sea. GrA-25815 is a date for an *Elephas antiquus* from the Southern Bight, dating 37,440 BP.

Apart from the official SIRI inter-comparison program which includes samples of all ages and materials, Pleistocene bones are often dated by more than one laboratory to compare protocols. This is particularly done for samples which are very important. Ample examples can be found in the literature. Of particular interest here is the so-called ultrafiltration method which was introduced to further purify (i.e. remove remaining contaminants) from bones treated by the classic so-called Longin method. However, the effectiveness of ultrafiltration is questioned (Huels *et al.*, 2009). This discussion still stands.

The laboratory intercomparisons show that for good quality bone, no additional treatments are necessary. Furthermore, we mention here a new development: compound specific dating. Separated amino acids from collagen, in particular hydroxyproline (known as HYP) are the most reliable datable fraction of (partially) degraded bone (Devièse *et al.*, 2018).

Another important methodological aspect is the dating limit of the ^{14}C method, and reporting dates close to that limit. The measurement errors become asymmetric, leading to the so-called 2-sigma criterion: when the measured activity becomes smaller than 2 times its measurement error, the age is given as this limit. As stated above, a proper background determination is essential as well.

In any case, dates like KIA-25281 reported with a finite age 54,010 BP (see Table 1) we consider not realistic.

A final remark concerning “anomalously young ^{14}C dates” relates to geophysical inferences and fits in other discussions on “too young” ^{14}C dates and their validity: North Sea shells. The datable fraction for these samples is their carbonate. In contrast to bones and other datable materials like wood, fossil corals and shells can recrystallize, enabling exchange of Carbon (including ^{14}C) from different sources. Shell ^{14}C dates therefore can be in conflict with other dating methods, in particular racemization.



Indeed, foraminifera of Eemian age can produce dates significantly younger than 50,000 BP. This open system behaviour appears to be species dependent, which was already known in the early days of Radiocarbon. Olsson (1989) described that infinitely old shells date 33,700 BP, corresponding to 1.5% contamination with modern Carbon. Most contamination remains in the outer part of the shells. Only in such cases, ^{14}C ages must be considered minimum ages (Busschers *et al.*, 2014).

This discussion concerning shell dates does not mean that obtaining good ^{14}C dates for carbonates are impossible, witness the very existence of the calibration curve IntCal20 (see Figure 1). The fact that the calibration curve exists back to 50,000 years ago alone is proof of that. But here fossil corals are used which suffer less (or not) from the problems (open system behaviour) mentioned above.

Discussion: Radiocarbon dates of human bones

Our database contains more than a hundred human skeletal remains with a North Sea context. This includes bones from the sea floor found by fishing or dredging as well as beach finds. In recent times the amount of beach finds strongly amplified because of the large sand suppletion projects along the coast of the province of Zuid Holland, in particular Maasvlakte 2 and Zandmotor.

A few years ago, an overview was published of 56 human bone finds (van der Plicht *et al.*, 2016). These have been submitted during the last decades for ^{14}C dating to the Groningen laboratory, of which both stable isotopes (^{13}C and ^{15}N) also have been measured. The main conclusions were that 33 were Mesolithic (including a few Late Palaeolithic), the dates of the remaining 23 range between Roman and recent times. The stable isotope analysis showed that the Mesolithic humans were predominantly consumers of freshwater protein.

Since this publication, the dataset has significantly grown in size. The updated set of ^{14}C dates is shown in Figure 3. A remarkable and significant observation is the gap in time; the fossils are either Mesolithic or

ranging between today and younger Roman times. There is only one exception at 5,020 BP (GrM-10161 from the island of Texel).

The stable isotope ratios $\delta^{13}\text{C}$ (and $\delta^{15}\text{N}$ when available) of the dated bones are discussed in an accompanying paper in this volume.

Conclusions

The North Sea region was dry land during the last glacial period, and was inhabited by a rich fauna. This yields large quantities of fossil bones recovered from the present seabed.

Over the years, more than 300 bones were dated by ^{14}C ; more than 200 for animals, and more than 100 for humans. These were dredged up from the sea bottom, or are found on the beach or on sand suppleted areas.

Since the finds are recovered without a clear context, the dates yield crucial information for reconstructions of the past environment in a multidisciplinary setting.

We discuss here all available dates from Groningen (and other laboratories when known to us) and show that most fossil bones provide important information on palaeontology, palaeoecology, landscape and archaeology for this unique heritage site.

Sample quality aspects are discussed and the background for fossil bone dating was set at 45,000 BP (ca. 47,000 calBP). Timescale calibration (presently covering the complete ^{14}C dating range) provides absolute dates.

Together with the stable isotope ratios $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, our analysis, based on a large database obtained over the years, illustrates that a collection of stray finds without context nevertheless can lead to inference of past environments in a multidisciplinary approach.

Further research, including ^{14}C dating and stable isotope measurements no doubt will increase our understanding of this important heritage site.

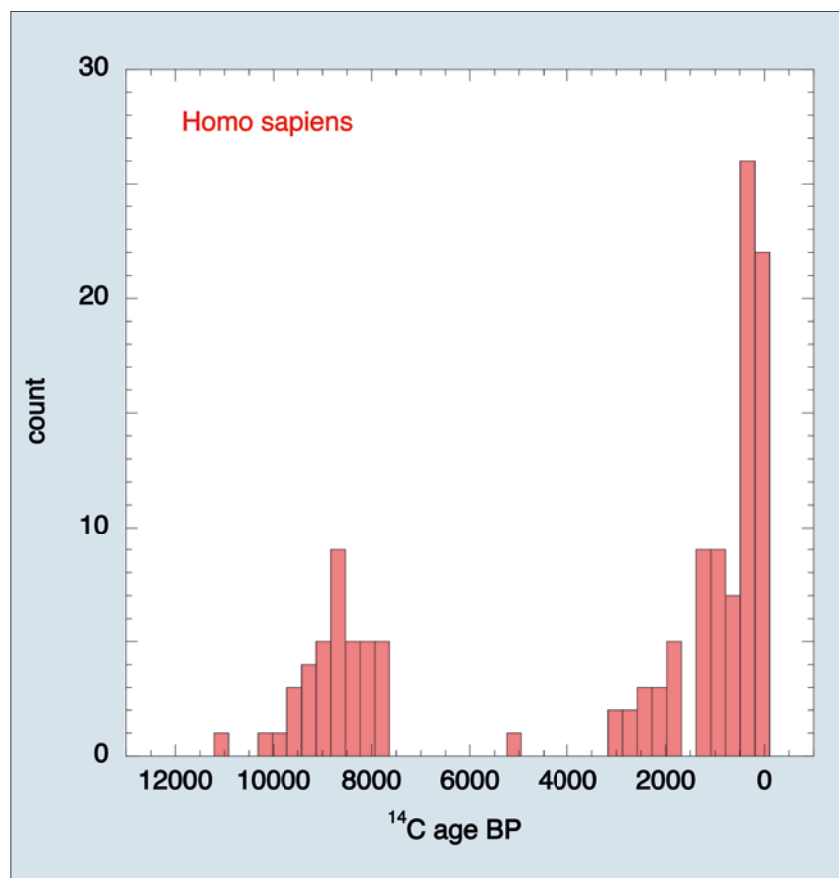


FIGURE 3. | Distribution of ^{14}C dates for human bones from the North Sea.



Samenvatting

Het radioactieve isotoop ^{14}C in fossiel bot.

Eén van de belangrijke vast te stellen parameters betreffende fossiele botmonsters is de ouderdom: wanneer leefde het organisme?

Ouderdommen kunnen worden gemeten met behulp van radioactieve isotopen; die zijn instabiel en vervallen in de loop van de tijd naar stabiele isotopen.

In de natuur komen drie isotopen van het element koolstof voor: ^{12}C , ^{13}C en ^{14}C . De isotopen ^{12}C en ^{13}C zijn stabiel en hebben een voorkomen van resp. ongeveer 98,9 en 1,1%. ^{14}C is radioactief en heeft een zeer geringe abundantie, ongeveer 10^{-10} %. De halveringstijd (tijd waarin de helft vervalt) van ^{14}C is 5730 jaar. Het wordt geproduceerd in de hogere atmosfeer door kosmische straling, reageert met zuurstof tot $^{14}\text{CO}_2$ en komt via fotosynthese in planten terecht, en daarmee ook in de voedselketen. Na de dood van een organisme stopt uiteraard de inname van voedsel; de hoeveelheid aanwezige ^{14}C neemt geleidelijk af in de tijd. Door de hoeveelheid resterende ^{14}C in een fossiel te meten kan het moment van overlijden worden vastgesteld.

Dat is een eenvoudig principe, maar in werkelijkheid is het een complexe zaak. Ten eerste is de ^{14}C concentratie in de atmosfeer niet constant, doordat de kosmische stralingsflux niet constant is; deze is afhankelijk van variaties in zonneactiviteit en geomagnetische veldsterkte.

Ten tweede zijn er effecten in natuurlijke processen die massa-afhankelijk zijn, en dus isotoop-afhankelijk. Bijvoorbeeld, bij fotosynthese wordt ^{12}C gemakkelijker opgenomen dan de zwaardere isotopen ^{13}C en ^{14}C . Planten bevatten daardoor minder ^{14}C dan de atmosfeer waarin ze groeien, en lijken daardoor ouder. Deze zogenaamde isotopenfractionering treedt op bij vrijwel alle fysische, chemische en biologische processen.

Ten derde waren er in het verleden onduidelijkheden betreffende de waarde van de halveringstijd.

Ten slotte is het ook niet eenvoudig om ^{14}C concentraties te meten, dat gebeurt tegenwoordig met deeltjesversnellers.

De hierboven genoemde complicaties zijn opgelost door de zogenaamde ^{14}C conventie, wat een vorm van standaardisatie is. Deze conventie houdt in:

1. de ^{14}C activiteit wordt gemeten relatief ten opzichte van die van een referentiemateriaal, welke gerelateerd is met het jaar AD 1950;
2. er wordt een halveringstijd van 5568 jaar gebruikt;
3. voor fractionering van ^{14}C wordt gecorrigeerd met behulp van die van het stabiele isotoop ^{13}C , gemeten voor hetzelfde monster;
4. de ^{14}C datering wordt uitgedrukt in de eenheid BP.

Hiermee is feitelijk voor ^{14}C een eigen tijdschaal gedefinieerd.

Voor meer technische achtergrond wordt naar de literatuur verwezen, bijvoorbeeld Mook & van der Plicht (1999).

Resteert het vaststellen van de relatie tussen BP en de kalender. Die is vastgelegd door middel van een ijkgrafiek. Deze is bepaald door het met ^{14}C dateren van monsters met een bekende ouderdom, zoals met name jaarringen van bomen welke zijn gedateerd met dendrochronologie. Voor het Pleistocene gedeelte leveren afzettingen met varven (gelaagde afzettingen waarbij elk laagje een jaar is) de belangrijkste ijkgegevens.

Met behulp van de ^{14}C methode kan worden gedateerd tot ca. 50,000 jaar geleden (dat komt overeen met ca. 47,000 BP). Ook hier wordt voor meer details naar de literatuur verwezen, met name Reimer *et al.* (2020) en de daarin vermelde referenties.

Het ^{14}C laboratorium van de Rijksuniversiteit Groningen behoort tot de oudste en nog steeds actieve laboratoria; de eerste dateringen zijn van 1952.

Voor het Noordzeegebied is gedurende de afgelopen decennia een aanzienlijke dateringslijst verkregen, die hier wordt bediscussieerd. De gegevens kunnen uniek worden genoemd: de lijst is aanzienlijk, en de Noordzee is als gebied erfgoed. De Groningse getallen zijn aangevuld met enkele dateringen van andere laboratoria, voor zover die ons bekend zijn.

Voor de fauna bevat de lijst meer dan 300 dateringen waarvan ca. 2/3 (laat) Weichselien, en 1/3 is Holoceen.

Daarnaast zijn ook menselijke resten gedateerd: archeologische monsters, maar het grootste gedeelte is afkomstig van opdrachten van het Nederlands Forensisch Instituut. Dat laatste is een categorie met de meeste aanwas van data; de meeste forensische dateringen zijn (sub)recent.

Voor de Noordzee is verreweg het meest gedateerde materiaal fossiel bot. Hiervan is collageen de dateerbare fractie. Het collageen moet van zo goed mogelijke kwaliteit zijn. Dat wordt vastgesteld door parameters zoals het gehalte van koolstof en stikstof (C% en N%). Als deze niet optimaal zijn kan er sprake zijn van degradatie, met als mogelijk gevolg contaminatie met koolstofhoudend materiaal wat niet afkomstig is van het bot zelf. De gevolgen hiervan zijn vooral van belang voor monsters met een hoge ouderdom.

Een ander probleem is museaal materiaal, wat meestal behandeld is met conserveermiddelen wat de datering vervuult als het niet is verwijderd. De meting van de ^{14}C concentratie is vrijwel altijd correct, maar de datering hoeft dat niet te zijn. Interpretatie van dergelijke dateringen is dan ook een probleem, mede ook omdat de monsters niet *in situ* zijn; ze zijn verspoeld, opgevisd of opgespoten. Dit verklaart mogelijk wat resultaten die in strijd lijken met aardwetenschappelijke gegevens.

Het ^{14}C bestand geeft voor de Noordzee door het grote aantal gegevens de parameter “tijd” voor archeologie (denk aan Doggerland en het Mesolithicum) en paleontologie (de rijke ijstijdfauna inclusief uitgestorven diersoorten zoals de mammoet).

A more concise version of this article for dating specialists is published in the journal Radiocarbon, DOI:10.1017/RDC.2022.9



lab code	locality	age BP	σ_1	σ_2	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
KIA-25281	North Sea	54010	2630	3940						>54500		<i>Delphinapterus leucas</i>	atlas		1
UtC-3751	Brown Bank	50000	2000	2800						>54500		<i>Odobenus rosmarus</i>	pelvis		1
UtC-3747	Outer Rough	50000	2000	3000						>54500		<i>Erignathus barbatus</i>	pelvis		1
UtC-3749	Denkmark, Helgoland	47400	1600	2100						>47350		<i>Odobenus rosmarus</i>	vertebra		1
UtC-7880	Borkum	46400	1700	1700						46080	52770	<i>Erignathus barbatus</i>	vertebra		1
GrA-32597	Eurogully	>45000			36.6	-19.1	15.1	2.9	2.8	>46790		<i>Rangifer tarandus</i>	metatarsal		2
GrA-20303	Brown Bank	>45000			39.7	-19.6				>46790		<i>Rangifer tarandus</i>	metacarpal		3
GrA-20475	Brown Bank	>45000			32.4	-19.6	15.2	2.9	2.5	>46790		<i>Rangifer tarandu</i>	unknown		2
GrN-28544	Southern Bight	>45000			40.5	-16.5				>46790		<i>Delphinapterus leucas</i>	vertebra		3
GrA-22179	Eurogully	>45000			40.9	-14.8	12.8	13.9	3.7	>46790		<i>Delphinapterus leucas</i>	axis		2
GrA-25849	Borkumrif	>45000			44.6	-14.4	17.3	16.5	3.0	>46790		<i>Delphinapterus leucas</i>	vertebra		a
GrA-22182	Eurogully	>45000			42.2	-14.4	14.8	13.3	3.3	>46790		<i>Eschrichtius robustus</i>	vertebra		a
GrA-34348	Zuid-Holland, Scheveningen	>45000			44.3	-14.8	16.6	12.9	3.1	>46790		<i>Eschrichtius robustus</i>	vertebra		a
GrA-34381	Southern Bight	>45000			42.1	-13.3	16.2	14.8	3.0	>46790		<i>Eschrichtius robustus</i>	axis		a
GrN-28546	Southern Bight	>45000			43.9	-15.8				>46790		<i>Pagophilus groenlandica</i>	humerus		3
UtC-7883	Brown Bank	>45000								>46790		<i>Pagophilus groenlandica</i>	femur		1
GrA-22178	Eurogully	>45000			45.6	-12.5	14.6	11.5	3.6	>46790		<i>Odobenus rosmarus</i>	cranium		a
GrN-28548	Southern Bight	>45000			41.9	-14.1				>46790		<i>Odobenus rosmarus</i>	femur		3
GrA-59468	Eurogully	>45000			42.2	-13.3	15.5	11.2	3.2	>46790		<i>Odobenus rosmarus</i>	mandible		a
GrA-50465	Brown Bank	>45000			43.0	-20.3	14.3	7.7	3.5	>46790		<i>Ursus arctos</i>	mandible		a
GrA-25816	Eurogully	>45000			35.9	-22.3	14.2	3.5	3.0	>46790		<i>Ursus species</i>	unknown		a
GrA-22183	Eurogully	>45000			43.4	-19.4	15.4	7.7	3.3	>46790		<i>Canis lupus</i>	femur		a
GrA-23151	Eurogully	>45000			39.9	-19.2	15.7	8.7	3.0	>46790		<i>Panthera spelaea</i>	ulna		a
GrA-56674	Zuid-Holland, Maasvlakte	>45000			40.0	-21.3	14.8	3.0	3.2	>46790		<i>Equus species</i>	tibia		a
GrA-30740	Zeeland, Westerschelde	>45000			46.9	-20.7	17.5	7.5	3.1	>46790		<i>Elephas antiquus</i>	unknown		a
GrA-30590	Zeeland, Westerschelde	>45000			48.7	-21.2	17.3	8.1	3.3	>46790		<i>Elephas antiquus</i>	unknown		a
GrA-30591	Zeeland, Westerschelde	>45000			45.5	-20.6	15.7	10.1	3.4	>46790		<i>Elephas antiquus</i>	unknown		a
GrA-30592	Zeeland, Westerschelde	>45000			41.6	-20.6	13.7	11.2	3.5	>46790		<i>Elephas antiquus</i>	unknown		a
GrA-56664	Zuid-Holland, Maasvlakte	>45000			39.1	-20.2	14.1	9.8	3.2	>46790		<i>Elephas antiquus</i>	cranium		a
GrA-38353	Eurogully	>45000			43.0	-20.6	15.2	6.6	3.3	>46790		<i>Megaloceros giganteus</i>	cranium		a
GrA-32601	Eurogully	>45000			45.7	-19.5	14.9	2.5	3.6	>46790		<i>Megaloceros giganteus</i>	antler		a
GrA-32685	Eurogully	>45000			40.5	-19.8				>46790		<i>Megaloceros giganteus</i>	unknown		3
GrA-34338	Southern Bight	>45000			40.9	-14.8	12.7	14.3	3.3	>46790		<i>Balaena mysticetus</i>	radius		a
GrA-37034	Southern Bight	>45000			46.0	-12.6				>46790		<i>Balaenoptera physalus</i>	thoracic vertebra		3
GrA-34524	Brown Bank	>45000			37.5	-21.9	13.2	6.1	3.3	>46790		Bovidae	unknown		a
GrA-34531	Brown Bank	>45000			39.2	-21.7	14.3	5.4	3.2	>46790		Bovidae	unknown		a
GrA-34533	Brown Bank	>45000			42.1	-21.9	15.1	6.7	3.2	>46790		Bovidae	unknown		a
GrN-28261	Eurogully	>45000			50.7	-19.6				>46790		<i>Bison priscus</i>	lental vertebra		2
GrA-37797	Stekels	>45000			45.9	-20.4	17.9	4.3	3.0	>46790		<i>Bos primigenius</i>	femur		a
GrN-32392	Eurogully	>45000			44.4	-20.7				>46790		<i>Coelodonta antiquitatis</i>	unknown		3
GrA-52410	Eurogully	>45000			35.3	-20.8	16.4	11.6	2.5	>46790		<i>Elephas antiquus</i>	molar root		2
GrA-59476	Brown Bank	>45000			42.7	-21.4	15.4	7.8	3.2	>46790		<i>Mammuthus primigenius</i>	tusk		a

TABLE 1. | Data for North Sea fossil animal bones, selected for Late Pleistocene and for infinite ^{14}C age (>45,000 BP). The table contains a column indicating the quality aspect of the measurement, wherein "a" means accepted, "1" accepted but not all criteria known, "2" not all criteria met but accepted, "3" accepted but only C isotopes measured.



lab code	locality	age BP	σ_1	σ_2	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
GrA-50851	Eurogully	>45000			47.9	-22.3	15.9	6.1	3.5	>46790		<i>Mammuthus primigenius</i>	tibia		a
GrA-50847	Eurogully	>45000			46.9	-22.1	15.8	6.2	3.5	>46790		<i>Mammuthus primigenius</i>	tibia		a
GrA-50854	Brown Bank	>45000			40.0	-21.7	14.8	7.2	3.1	>46790		<i>Mammuthus primigenius</i>	tooth		a
GrA-50860	Brown Bank	>45000			41.3	-21.5	14.3	9.0	3.4	>46790		<i>Mammuthus primigenius</i>	tooth		a
GrA-50848	North Sea	>45000			43.2	-22.2	13.4	8.3	3.7	>46790		<i>Mammuthus primigenius</i>	tooth		2
GrA-52416	Brown Bank	>45000			46.0	-21.6	15.9	9.1	3.4	>46790		<i>Mammuthus primigenius</i>	tooth		a
GrA-50846	Brown Bank	>45000			40.3	-22.4	15.2	8.0	3.1	>46790		<i>Mammuthus primigenius</i>	tooth		a
GrA-50843	Brown Bank	>45000			45.1	-22.4	14.1	8.4	3.7	>46790		<i>Mammuthus primigenius</i>	tooth		2
GrA-11640	Brown Bank	>45000			47.9	-22.4				>46790		<i>Mammuthus primigenius</i>	epistropheus		3
GrA-56656	Brown Bank	>45000			40.3	-21.9	14.9	5.9	3.2	>46790		<i>Mammuthus primigenius</i>	unknown		a
GrA-56660	Eurogully	>45000			39.6	-21.9	14.6	5.6	3.2	>46790		<i>Mammuthus primigenius</i>	humerus	hyena bitemarks	a
GrA-56661	Eurogully	>45000			41.4	-21.8	15.1	5.7	3.2	>46790		<i>Mammuthus primigenius</i>	humerus		a
GrA-56675	Zuid-Holland, Maasvlakte	>45000			41.8	-21.6	15.4	5.0	3.2	>46790		<i>Mammuthus primigenius</i>	femur		a
GrA-43620	Stekels	>45000			36.6	-23.0	13.7	4.6	3.1	>46790		unknown	unknown	possible artifact	a
GrA-40522	Brown Bank, SW	>45000			38.9	-20.6	14.4	5.2	3.2	>46790		unknown	cf tibia	marrow expl?	a
GrA-39965	Great Yarmouth	>45000			42.0	-20.6	4.8	4.5	3.3	>46790		<i>Coelodonta antiquitatis</i>	mandible	soxhlet	a
GrA-20475	Brown Bank	>45000			32.4	-19.6				>46790		<i>Rangifer tarandus</i>	bone		3
GrA-42704	Southern Bight	>45000			36.4	-21.4	12.7	6.4	3.3	>46790		<i>Equus species</i>	metacarpal	donkey, palaeo- lithic	a
GrA-23582	Brown Bank	44780	1550	1920	40.7	-21.4	14.4	5.4	3.3	44580	54330	<i>Equus caballus</i>	tibia		a
GrA-23581	Brown Bank	44560	1490	1840	43.9	-20.4	15.3	4.7	3.3	44450	54280	<i>Alces alces</i>	antler		a
GrA-20254	Eurogully/ Brown Bank	44100	1100	1250	41.1	-19.1				44630	49600	<i>Rangifer tarandus</i>	calcaneum		3
GrA-56662	Eurogully	43910	450	550	43.4	-21.8	15.9	6.5	3.2	45310	47570	<i>Mammuthus primigenius</i>	ulna		a
GrA-20134	Eurogully	43800	550	600	39.7	-22.4				45100	47600	<i>Mammuthus primigenius</i>	fibula		3
GrA-22585	Eurogully	43550	1050	1200	44.5	-22.0	16.5	2.3	3.1	44410	48700	<i>Equus species</i>	ulna		a
GrN-28547	Southern Bight	>43500			40.1	-15.0				>45900		<i>Pagophilus groenlandica</i>	humerus	reservoir effect	3
GrA-64453	Zuid-Holland, Hoek van Holland	43290	380	400	39.9	-14.9	14.5	17.6	3.2	44890	46460	<i>Pinguinus impennis</i>	humerus	reservoir effect	a
GrA-39964	Great Yarmouth	42960	420	500	38.2	-21.4	14.1	4.1	3.2	44650	46180	<i>Equus species</i>	metacarpal	soxhlet	a
GrN-28549	Southern Bight	42800	2700	4100	42.3	-15.4				42630	54970	<i>Eschrichtius robustus</i>	vertebra	reservoir effect	3
GrA-50866	Brown Bank	42690	470	550	39.1	-21.4	14.8	6.6	3.1	44520	46060	<i>Mammuthus primigenius</i>	tooth		a
GrA-40013	Zeeland, Westerschelde	42400	800	1100	36.6	-20.5	13.1	11.1	3.3	43360	47060	<i>Elephas antiquus</i>	mandible	soxhlet	a
GrA-20259	Brown Bank	42300	900	1000	36.3	-18.9	13.8	3.2	3.1	43300	46940	<i>Rangifer tarandus</i>	astragalus		a
GrA-21327	Brown Bank	41970	700	920	44.3	-19.0				43240	46120	<i>Rangifer tarandus</i>	radius	duplicate 20260	3
GrA-50858	Brown Bank	41450	420	490	44.7	-22.4	13.7	8.8	3.8	43330	45050	<i>Mammuthus primigenius</i>	tooth		2
GrM-24067	Terneuzen	>41400			38.3	-20.5	14.1	5.5	3.2	>44100		<i>Coelodonta antiquitatis</i>			a
GrM-24068	Terneuzen	>41400			40.1	-21.6	14.9	3.2	3.1	>44100		<i>Coelodonta antiquitatis</i>			a
GrM-24070	Terneuzen	>41400			43.0	-21.4	15.6	7.5	3.2	>44100		<i>Equus species</i>			a
GrM-24073	Terneuzen	>41400			41.5	-20.4	15.3	3.2	3.2	>44100		<i>Mammuthus primigenius</i>			a
GrM-24074	Terneuzen	>41400			40.6	-21.9	14.9	5.3	3.2	>44100		<i>Mammuthus primigenius</i>			a
GrM-24188	Terneuzen	>41400			33.9	-22.2	12.4	8.1	3.2	>44100		<i>Mammuthus primigenius</i>			a
GrM-24189	Terneuzen	>41400			41.0	-21.8	15.0	7.0	3.2	>44100		<i>Mammuthus primigenius</i>			a



lab code	locality	age BP	σ_1	σ_2	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
GrA-20260	Brown Bank	41200	800	900	39.8	-19.1	14.4	5.1	3.2	42880	45530	<i>Rangifer tarandus</i>	radius		a
AA-17634	Brown Bank	>41100								>44190		<i>Mammuthus primigenius</i>	tooth		1
GrA-56655	North Sea	41090	350	400	36.4	-22.1	13.3	6.1	3.2	43240	44640	<i>Mammuthus primigenius</i>	unknown		a
GrA-32599	Eurogully	40750	380	440	38.7	-20.1	14.2	5.5	3.2	43060	44470	<i>Megaloceros giganteus</i>	antler		a
GrA-11643	Brown Bank	40660	350	350	39.3	-20.1				43070	44380	<i>Crocota crocuta spelaea</i>	ulna		3
GrA-34337	Zeeland, Yerseke	40550	350	400	40.5	-16.4	14.7	15.1	3.1	43000	44340	<i>Delphinapterus leucas</i>	mandible		a
GrA-64644	Denmark, Holmgren	40360	230	240	39.1	-13.9	15.3	12.0	3.0	42980	44110	<i>Odobenus rosmarus</i>	atlas	reservoir effect	a
GrM-24066	Terneuzen	40100	1200	1400	40.1	-21.4	14.7	5.7	3.2	42070	46220	<i>Mammuthus primigenius</i>			a
AA-17635	Brown Bank	>40000								>43070		<i>Mammuthus primigenius</i>	vertebra		1
GrA-50864	North Sea	39970	380	440	34.9	-21.7	13.3	7.9	3.1	42690	44100	<i>Mammuthus primigenius</i>	tooth		a
GrA-31471	North Sea	39970	320	360	41.5	-19.4	13.9	8.2	3.5	42730	44020	<i>Panthera spelaea</i>	scapula		a
GrN-27411	Eurogully	39910	950	1070	45.8	-20.8				42290	44870	<i>Coelodonta antiquitatis</i>	pelvis		3
GrA-39518	Great Yarmouth	39900	650	850	35.6	-20.9				42460	44420	<i>Bison</i> species	metacarpale	soxhlet	3
GrA-56658	Brown Bank	39860	310	350	41.2	-21.5	15.1	7.2	3.2	42660	43960	<i>Mammuthus primigenius</i>	femur	SIRI	a
AA-17637	Brown Bank	39800	3400	3400						40620	55500	<i>Mammuthus primigenius</i>	vertebra		1
GrA-21326	Eurogully/ Brown Bank	39770	650	700	41.1	-19.2				42450	44290	<i>Rangifer tarandus</i>	calcaneum	duplicate 20254	3
GrA-21419	Brown Bank	39700	1700	2100	42.2	-19.1	14.7	4.4	3.3	41140	48720	<i>Rangifer tarandus</i>	metacarpal	duplicate 20255	a
AA-17639	Brown Bank	>39300								>42750		<i>Mammuthus primigenius</i>	carpal bones		1
GrA-20257	Eurogully	39200	650	700	35.9	-21.2	13.7	6.8	3.1	42230	44020	<i>Rangifer tarandus</i>	phalanx		a
GrA-20255	Brown Bank	39150	650	700	40.9	-19.1	17.6	4.3	2.7	42210	43990	<i>Rangifer tarandus</i>	metacarpal		2
GrA-34349	Eurogully	39100	320	360	41.6	-14.0	13.3	12.2	3.6	42380	43010	<i>Eschrichtius robustus</i>	atlas	reservoir effect	a
GrA-20261	Brown Bank	39000	600	700	39.0	-19.2	14.1	4.3	3.2	42150	43880	<i>Rangifer tarandus</i>	epistropheus		a
AA-17636	Brown Bank	>39000								>42620		<i>Mammuthus primigenius</i>	fibula		1
GrA-50852	Eurogully	38960	350	400	38.6	-22.4	13.8	7.3	3.3	42310	42970	<i>Mammuthus primigenius</i>	vertebra		a
GrA-31284	Brown Bank	38960	355	355	35.1	-19.8	13.2	3.6	3.1	42320	42970	<i>Rangifer tarandus</i>	antler	artifact	a
AA-17638	Brown Bank	>38900								>42500		<i>Mammuthus primigenius</i>	carpal bones		1
AA-17648	Brown Bank	>38600								>42470		<i>Mammuthus primigenius</i>	tooth		1
UtC-3752	Westhinder	38500	800	800						41770	43900	<i>Delphinapterus leucas</i>	vertebra	reservoir effect	1
AA-17642	Brown Bank	37900	2800	2800						37730	52520	<i>Mammuthus primigenius</i>	tooth		1
GrA-37558	Stekels	37860	355	355	41.9	-19.9	16.3	4.8	3.0	41910	42510	<i>Equus caballus</i>	metacarpal	artefact	a
GrN-27410	Eurogully	37580	740	810	45.6	-21.7				41130	42830	<i>Mammuthus primigenius</i>	cranium		3
GrA-25815	Southern Bight	37440	310	310	42.3	-20.3	11.9	15.0	3.5	41660	42360	<i>Elephas antiquus</i>	unknown		1
GrA-39962	Great Yarmouth	37240	260	280	27.5	-22.6				41550	42250	<i>Mammuthus primigenius</i>	vertebra	soxhlet	3
AA-17647	Brown Bank	36800	2400	2400						36780	49390	<i>Mammuthus primigenius</i>	tooth		1
GrA-11641	Brown Bank	36740	230	230	42.5	-20.1				41270	42010	<i>Ovibos moschatus</i>	metacarpal		3
OxA- 6308	Brown Bank	36300	1100	1100						39460	42580	<i>Megaloceros giganteus</i>	metacarpal		1
AA-17643	Brown Bank	>36200								>41220		<i>Mammuthus primigenius</i>	tooth		1
OxA- 6307	Brown Bank	35600	1200	1200						38150	42490	<i>Ovibos moschatus</i>	metacarpal		1
AA-17645	Brown Bank	35200	2000	2000						36140	44420	<i>Mammuthus primigenius</i>	tooth		1
GrA-25570	Brown Bank	35160	315	315	36.0	-19.3	12.6	2.2	3.3	39660	40980	<i>Rangifer tarandus</i>	antler		a
UtC-3753	Brown Bank	34600	500	400						39230	40480	<i>Delphinapterus leucas</i>	humerus	reservoir effect	1
AA-17634	Brown Bank	33800	1200	1200						36190	41340	<i>Mammuthus primigenius</i>	metacarpal		1
GrA-39966	Great Yarmouth	31460	150	160	42.8	-19.5	14.4	2.5	3.5	35430	36180	<i>Rangifer tarandus</i>	antler	soxhlet	a
UtC-10999	Brown Bank	31300	400	400		-17.6				34760	36410	<i>Homotherium latidens</i>	tooth	same animal	1
UtC-10456	Brown Bank	31300	400	400		-18.1				34760	36410	<i>Homotherium latidens</i>	tooth	same animal	1



lab code	locality	age BP	σ_1	σ_2	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
GrA-54021	Zuid-Holland, Zandmotor	31140	190	200	32.3	-21.3				35110	36110	<i>Lepus</i> species	mandible		3
K-3726	Denmark	30880	1110	1270						33120	39160	<i>Odobenus rosmarus</i>	cranium	reservoir effect	1
GrA-69520	Zuid-Holland, Zandmotor	29900	490	550	34.3	-20.7	12.5	8.5	3.2	33240	35450	<i>Alopex lagopus</i>	unknown		a
GrA-20294	Eurogully/ Brown Bank	29460	250	250	38.5	-19.4	15.7	4.1	2.9	33380	34470	<i>Rangifer tarandus</i>	astragalus		a
GrA-50454	Eurogully	28740	180	190	45.5	-26.4				32220	33740	<i>Protophormia terraenovae</i>	chitine	pup blowfly	a
UtC-11000	Brown Bank	28100	220	220		-21.2				31600	32990	<i>Homotherium latidens</i>	tooth	same animal	1
UtC-11065	Brown Bank	27650	280	280		-17.7				31110	32740	<i>Homotherium latidens</i>	mandible	same animal	1
GrA-26887	Eurogully	27510	180	190	no data	-14.7				31150	31780	<i>Pagophilus groenlandica</i>	sacrum	reservoir effect	1
UtC-10908	Brown Bank	26900	400	400		-18.9				30250	31740	<i>Homotherium latidens</i>	mandible	same animal	1
UtC-11064	Brown Bank	26700	240	240		-15.3				30360	31200	<i>Homotherium latidens</i>	mandible	same animal	1
GrA-65933	Zuid-Holland, Maasvlakte 2	25130	130	130	26.2	-15.5	9.3	14.5	3.3	29130	29850	<i>Halichoerus grypus</i>	unknown	reservoir effect	2
GrA-33828	Eurogully	24670	150	160	19.0	-23.4						<i>Castor fiber</i>	femur		r
K-3727	Denmark	24380	620	620						27490	30000	<i>Odobenus rosmarus</i>	cranium	reservoir effect	1
K-4473	Denmark	23500	460	460						26960	28820	<i>Odobenus rosmarus</i>	cranium	reservoir effect	1
GrA-37536	Brown Bank	15360	90	90	38.1	-19.5				18300	18850	Caprinae	unknown	same animal	3
GrA-38211	Brown Bank	15190	60	60	37.0	-19.2	14.1	7.5	3.0	18280	18670	Caprinae	unknown	same animal	a
GrA-37800	Brown Bank	15120	50	50	38.3	-19.2				18240	18650	Caprinae	unknown	same animal	3

lab code	locality	age BP	σ	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
GrA-28364	Brown Bank	11560	50	37.9	-20.6	14.5	3.9	3.1	13315	13575	<i>Bison</i> species	metatarsus	decorated	a
GrA-34644	Brown Bank	10730	60	33.9	-21.2				12620	12765	<i>Gulo gulo</i>	mandible		3
GrA-36110	Brown Bank	10000	50	44.4	-21.1	14.8	3.7	3.5	11265	11730	<i>Cervus elaphus</i>	antler	artifact	a
GrA-27206	Brown Bank	9910	50	39.9	-20.9	16.6	1.7	2.8	11210	11610	<i>Alces alces</i>	antler	artifact	2
GrA-37796	Stekels	9815	40	42.9	-21.2	15.1	3.5	3.3	11175	11310	<i>Cervus elaphus</i>	antler		a
GrA-37795	Stekels	9675	40	43.7	-20.8	16.5	4.1	3.1	10800	11205	<i>Cervus elaphus</i>	antler	artifact	a
GrA-37004	Brown Bank	9520	50	39.7	-21.7	14.1	3.4	2.8	10595	11090	<i>Alces alces</i>	antler	artifact	2
GrA-68250	Zuid-Holland	9510	50	44.3	-20.6	16.2	2.2	3.2	10585	11080	<i>Alces alces</i>	antler		a
GrA-25514	North Sea	9500	180	41.5	-21.5				10290	11235	<i>Cervus elaphus</i>	antler		3
UtC-7886	Brown Bank	9450	70						10500	11075	<i>Sus scrofa</i>	humerus		1
GrA-29203	Brown Bank	9350	60	20.4	-22.3						<i>Capreolus capreolus</i>	antler		r
OxA-13425	Southern Bight	9305	70						10275	10690	<i>Sus scrofa</i>	unknown		1
OxA-13426	Southern Bight	9290	65						10255	10655	<i>Sus scrofa</i>	unknown		1
GrA-51667	North Sea	9220	40	38.6	-22.7	14.7	4.9	3.1	10250	10500	Bovidae	metacarpal	artifact	a
GrA-30732	Brown Bank	9070	50	40.6	-21.9	14.5	5.0	3.3	10155	10380	<i>Cervus elaphus</i>	tibia	artifact	a

TABLE 2. | Data for North Sea fossil animal bones, selected for Holocene age. The table contains a column indicating the quality aspect of the measurement, wherein "a" means accepted, "1" accepted but not all criteria known, "2" not all criteria met but accepted, "3" accepted but only C isotopes measured.



lab code	locality	age BP	σ	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
GrA-40524	Eurogully	9070	45	38.1	-21.6	13.7	3.2	3.2	10170	10375	<i>Cervus elaphus</i>	antler	artifact	a
GrA-43612	Stekels	8945	45	34.8	-22.8	13.9	5.4	2.9	9905	10225	unknown	bone	artifact	a
GrA-30722	Brown Bank	8910	50	45.1	-21.1	16.5	4.8	3.2	9795	10205	<i>Castor fiber</i>	femur		a
GrA-51668	North Sea	8900	40	44.3	-22.4	15.6	5.2	3.3	9820	10195	<i>Bos primigenius</i>	unknown	artifact	a
GrA-31283	Brown Bank	8880	40	38.9	-22.2	12.8	2.4	3.6	9780	10185	<i>Capreolus capreolus</i>	tibia		a
GrA-29204	Brown Bank	8870	50	42.4	-22.2				9755	10185	<i>Cervus elaphus</i>	antler	artifact	3
GrA-34339	Southern Bight	8860	40	39.1	-21.9				9765	10175	<i>Sus scrofa</i>	mandible		3
GrA-37561	Stekels	8830	40	44.2	-21.7	15.2	2.5	3.4	9695	10150	<i>Cervus elaphus</i>	antler	artifact	a
GrA-52432	Eurogully	8825	45	39.4	-24.8				9685	10155	<i>Lutra lutra</i>	cranium		3
GrA-20256	Brown Bank	8820	60	40.6	-22.7	16.8	4.0	2.8	9625	10170	<i>Rangifer tarandus</i>	phalanx		2
GrA-25569	Brown Bank	8800	50	38.2	-22.3	14.7	5.2	3.0	9560	10150	<i>Bos primigenius</i>	metapodal	modified	a
GrA-24209	Eurogully	8780	50	47.7	-25.6	16.7	10.2	3.3	9550	10120	<i>Canis species</i>	cranium		a
GrA-22998	Brown Bank	8780	60	36.2	-22.6	15.5	5.5	2.7	9550	10125	<i>Bos primigenius</i>	metacarpal	artifact	2
GrA-32600	Eurogully	8710	45	41.7	-21.2	15.1	4.0	3.2	9540	9890	<i>Sus scrofa</i>	humerus		a
GrA-36113	Brown Bank	8710	50	39.7	-22.5	13.4	2.2	3.5	9540	9890	<i>Cervus elaphus</i>	antler	artifact	a
GrA-59743	Zuid-Holland, Maasvlakte	8680	60	37.8	-19.6	13.9	4.2	3.2	9535	9890	unknown	unknown	harpoon	a
GrA-30795	Brown Bank	8660	50	45.7	-21.9	16.1	5.3	3.3	9530	9765	unknown	metapodal	artifact	a
GrA-25568	Southern Bight	8600	50	36.6	-21.8	13.9	2.1	3.1	9485	9690	<i>Cervus elaphus</i>	antler	modified	a
GrA-33949	Eurogully	8405	45	36.8	-21.4	12.5	3.0	3.4	9300	9530	<i>Capreolus capreolus</i>	antler	artifact	a
GrA-20353	Brown Bank	8350	50	30.6	-23.3				9140	9485	<i>Rangifer tarandus</i>	phalanx		3
GrA-52433	Zuid-Holland, Maasvlakte 2	8300	40	32.0	-26.2	13.3	8.6	2.8	9135	9440	<i>Lutra lutra</i>	mandible		2
GrA-42195	Zuid-Holland, Rockanje	8295	45	42.4	-22.1	13.1	6.3	3.8	9130	9440	unknown	unknown		2
GrA-30731	Brown Bank	8240	50	45.8	-21.2	16.4	4.2	3.3	9025	9410	<i>Alces alces</i>	antler	artifact	a
GrA-51786	Eurogully	8175	40	42.8	-22.8	16.6	6.1	3.0	9010	9275	<i>Bos primigenius</i>	horn pit		a
GrA-25851	Southern Bight	8135	45	40.0	-11.4	15.6	15.9	3.0	8990	9270	<i>Tursiops truncatus</i>	mandible	reservoir effect	a
GrA-22999	Eurogully	8070	50	38.5	-20.4	16.0	3.4	2.8	8720	9195	<i>Cervus elaphus</i>	antler	modified	2
GrA-23201	Eurogully	7970	60	25.6	-26.9						<i>Alces alces</i>	antler		r
GrA-30974	Zeeland, Westerschelde	7900	60	0.5	-23.1						<i>Odobenus rosmarus</i>	unknown	reservoir effect	r
GrA-30721	Eurogully	7780	50	31.9	-21.9	13.4	6.2	2.8	8420	8645	<i>Sus scrofa</i>	atlas		2
GrA-25850	Southern Bight	7390	50	43.5	-12.4	16.0	14.9	3.2	8035	8345	<i>Tursiops truncatus</i>	mandible	reservoir effect	a
UtC-7885	Brown Bank	7270	60						7965	8190	<i>Tursiops truncatus</i>	vertebra	reservoir effect	1
GrN-28551	Southern Bight	7180	60	38.7	-11.7				7865	8170	<i>Halichoerus grypus</i>	bone	reservoir effect	3
GrA-64384	Zuid-Holland, Zandmotor	6480	40	35.5	-14.3	12.9	17.7	3.2	7585	7780	<i>Pinguinus impennis</i>	humerus	reservoir effect	a
OxA-13427	Southern Bight	5455	70						6005	6400	<i>Sus scrofa</i>	unknown		1
GrA-34378	North Sea	4815	40	40.4	-14.0	16.2	13.9	2.9	5465	5605	<i>Eschrichtius robustus</i>	cranium		a
GrA-34342	Wadden Sea	4550	35	45.2	-12.3	17.1	15.4	3.1	5050	5435	<i>Orcinus orca</i>	maxila	reservoir effect	a
GrA-34380	Southern Bight	4230	35	46.8	-15.0	14.6	14.5	3.7	4625	4860	<i>Eschrichtius robustus</i>	vertebra	reservoir effect	2
GrN-31093	Noord-Holland, Andijk	4130	40	39.1	-14.1				4525	4825	<i>Eschrichtius robustus</i>	unknown	reservoir effect	3
GrA-34761	Southern Bight	4055	35	46.7	-14.6	13.8	16.0	3.4	4420	4795	<i>Eschrichtius robustus</i>	unknown	reservoir effect	a
GrA-20280	Zeeland, Roompot	4030	60	32.2	-22.6				4295	4815	<i>Cervus elaphus</i>	antler	axe	3
GrA-34379	North Sea	3925	35	42.2	-13.1	16.6	14.0	3.0	4240	4510	<i>Eschrichtius robustus</i>	cranium	reservoir effect	a
GrA-25820	Southern Bight	3900	45	38.7	-11.6	14.4	17.4	3.1	4490	4510	<i>Orcinus orca</i>	unknown	reservoir effect	a
GrA-34385	Southern Bight	3650	35	47.2	-13.4	17.4	14.6	3.2	3870	4090	<i>Eschrichtius robustus</i>	vertebra	reservoir effect	a
GrA-50510	North Sea	3540	40	42.5	-22.6	14.6	5.1	3.4	3695	3960	<i>Cervus elaphus</i>	antler	artifact	a
GrA-65546	Zuid-Holland, Zandmotor	3505	35	39.4	-14.2	13.8	16.0	3.3	3645	3880	<i>Pinguinus impennis</i>	unknown	reservoir effect	a



lab code	locality	age BP	σ	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N ratio	calBP low	calBP high	species	skeletal element	remarks	quality
GrA-26885	Southern Bight	3335	35	no data	-13.1				3465	3685	<i>Phocaena phocaena</i>	atlas	reservoir effect	1
GrA-25852	Southern Bight	3120	40	39.8	-12.0	14.7	15.6	3.2	3220	3445	<i>Lagenorhynchus albirostris</i>	mandible	reservoir effect	a
GrA-37555	Stekels	2505	35	43.2	-12.4	15.0	16.2	3.4	2460	2740	<i>Lagenorhynchus albirostris</i>	vertebra	reservoir effect	a
GrA-34383	Southern Bight	2270	35	45.0	-14.6	16.1	12.5	3.3	2155	2350	<i>Eschrichtius robustus</i>	axis	reservoir effect	a
GrA-66408	Yerseke	2190	30	39.4	-16.7	13.4	9.3	3.4	2110	2320	<i>Balaenidae</i>	bulla	reservoir effect	a
GrA-57505	Eurogully	2070	30	43.7	-12.9	16.9	13.6	3.0	1940	2120	<i>Odobenus rosmarus</i>	tooth	neolithic axe reservoir effect	a
UtC-7884	White Bank	1921	35						1735	1930	<i>Eschrichtius robustus</i>	mandible	reservoir effect	1
GrA-34369	White Bank	1870	35	43.6	-15.1	17.0	16.1	3.0	1705	1875	<i>Eschrichtius robustus</i>	mandible	reservoir effect	a
GrA-34368	North Sea	1865	30	42.8	-14.9	15.6	15.9	3.2	1705	1865	<i>Eschrichtius robustus</i>	vertebra	reservoir effect	a
KIA-25282	Wadden Sea, Terschelling	1645	25						1410	1685	<i>Eschrichtius robustus</i>	mandible	reservoir effect	1
KIA-25282	Wadden Sea, Terschelling	1530	90						1285	1685	<i>Eschrichtius robustus</i>	mandible	reservoir effect duplicate	1
GrA-22093	Zeeland, Roompot	1370	40	37.1	-20.9				1175	1350	<i>Cervus elaphus</i>	unknown	duplicate GrA-20291	3
GrA-20291	Zeeland, Roompot	1310	60	36.9	-20.5				1070	1340	<i>Cervus elaphus</i>	antler	carved face	3
GrA-34526	Brown Bank	110	50	45.2	-21.8	15.9	5.1	3.3	5	280	Bovidae		unknown	a

lab code	locality	age BP	σ	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N	skeletal element	remarks
GrA-58271	Zuid-Holland, Maasvlakte	11050	45	41.6	-20.6	14.9	9.7	3.3	bone	
GrA-42700	Southern Bight	10070	50	36.0	-24.7	13.3	11.2	3.2	cranium	
GrA-23205	North Sea	9870	70	5.9	-25.3				mandible	quality sample not good
UtC-3750	Brown Bank	9640	400						cranium	
GrA-42702	Southern Bight	9440	50	41.5	-24.2	15.6	13.6	3.1	cranium	
GrA-57506	Eurogully/Brown Bank	9440	45	40.3	-24.4	15.1	12.2	3.1	femur	
GrA-50459	Eurogully	9220	60	35.4	-22.8	13.1	10.0	3.2	femur	
GrA-62470	Zuid-Holland, Maasvlakte	9180	50	42.7	-23.0	16.2	10.3	3.1	cranium	
GrA-49638	North Sea	9150	50	44.5	-22.7	16.3	4.5	3.2	bone	
GrA-27188	Brown Bank	9140	50	36.4	-23.1	15.4	10.2	2.8	humerus	
GrA-30733	Brown Bank	9080	50	42.6	-22.0	15.3	11.6	3.2	bone	
GrA-31287	Brown Bank	9035	40	33.2	-23.4	12.3	11.4	3.2	bone	
GrA-35949	Brown Bank	9005	45	40.7	-23.3	14.1	10.8	3.4	humerus	
GrA-62225	Eurogully	8945	45	40.4	-13.4	15.0	14.1	3.1	humerus	
GrA-51669	North Sea	8910	40	43.7	-22.1	15.7	9.4	3.2	bone	
GrA-49637	North Sea	8820	50	44.1	-22.5	13.9	9.3	3.7	bone	
GrA-67124	Zuid-Holland, Zandmotor	8680	45	44.0	-23.6	16.1	12.4	3.2	cranium	
GrA-45801	Brown Bank	8665	45	43.6	-16.5	15.3	15.7	3.3	femur	
GrA-54734	Eurogully	8660	50	46.3	-23.9	15.0	12.4	3.6	femur	duplo 54733
GrA-54735	North Sea	8660	50	43.1	-16.7	15.6	13.8	3.2	femur	
M-21188	Zuid-Holland, Hoek van Holland	8630	25	51.3	-23.4	18.0	14.1	3.3	tooth	
GrA-57501	Zuid-Holland, Maasvlakte	8565	45	37.3	-23.5	14.0	12.7	3.1	cranium	
GrA-54733	Eurogully	8560	50	43.0	-24.1	15.4	12.4	3.3	femur	duplo 54734
GrA-65508	Slijtgeul	8560	50	30.5	-19.8	11.2	12.9	3.2	maxilla	

TABLE 3. | Data for North Sea human bones, all ages. The table contains a column indicating the quality aspect of the measurement, wherein "a" means accepted, "1" accepted but not all criteria known, "2" not all criteria met but accepted, "3" accepted but only C isotopes measured.



lab code	locality	age BP	σ	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N	skeletal element	remarks
GrA-56366	Zuid-Holland, Hoek van Holland	8425	40	37.4	-21.3	14.2	14.9	3.1	tooth	
GrA-63432	Zuid-Holland, Hoek van Holland	8375	45	34.0	-23.1	12.8	12.5	3.1	cranium	
GrA-11642	North Sea	8370	50	39.0	-15.6	14.3	15.7	3.2	mandible	
UtC-624	Brown Bank	8340	130						frontal bone	
GrA-56352	Zeeland, Burgh Haamstede	8290	40	42.0	-19.9	15.7	15.0	3.1	tooth	
GrA-27205	Brown Bank	8180	45	40.6	-22.6	17.7	15.1	2.7	femur	
GrA-65943	Zuid-Holland, Zandmotor	8140	45	39.1	-22.5	14.0	15.9	3.3	cranium	
GrM-10211	Noord-Holland, Castricum	8000	45	43.2	-16.9	15.5	17.4	3.2	bone	
GrA-51670	North Sea	7955	40	43.3	-21.5	15.6	14.6	3.2	bone	
GrA-68069	North Sea	7950	45	43.0	-17.6	15.7	16.2	3.2	tooth	
GrA-63431	Zuid-Holland, Monster	7885	45	38.4	-21.3	15.0	14.1	3.0	cranium	
GrA-63799	Zuid-Holland, Maasvlakte	7870	45	40.8	-23.7	15.0	12.9	3.2	cranium	
GrA-67123	Zuid-Holland, Zandmotor	7810	45	41.5	-20.9	15.1	15.6	3.2	cranium	
GrA-65507	Zuid-Holland, Zandmotor	7760	45	36.3	-21.6	13.1	16.4	3.2	femur	
GrA-68591	Zuid-Holland, Den Haag	7725	45	44.8	-23.2	16.3	13.9	3.2	cranium	
GrM-10161	Wadden Sea, Texel	5020	25	45.8	-21.0	16.7	9.6	3.2	cranium	
GrM-10748	Noord-Holland, Bloemendaal	3130	20	44.9	-20.2	16.4	13.4	3.2	vertebra	
GrM-10746	Noord-Holland, Noordwijk	2985	20	46.3	-20.2	16.9	8.0	3.2	femur	
GrM-12352	Noord-Holland, Noordwijk	2842	16	44.0	-20.2	16.0	9.5	3.2	humerus	
GrA-65511	Wadden Sea, Terschelling	2740	35	40.5	-20.4	14.1	10.2	3.3	vertebra	
GrA-67067	North Sea	2285	30	42.3	-20.4	15.5	11.3	3.2	vertebra	
GrA-68058	Zuid-Holland, Den Haag	2190	30	38.0	-19.6	13.9	12.2	3.2	tooth	
GrM-12817	Wadden Sea, Texel	2156	15	44.0	-19.4	15.9	11.7	3.2	cranium	
GrA-69134	Zuid-Holland, Katwijk	1995	30	45.2	-20.2	16.4	10.4	3.2	scapula	
GrA-63619	Wadden Sea, Terschelling	1830	30	44.2	-19.9	16.6	9.9	3.1	bone	
GrA-64747	Noord-Holland, Zaandam	1805	30	46.4	-20.2	16.9	9.9	3.2	femur	
GrA-64726	Zeeland, Borsele	1335	30	41.9	-19.4	15.2	12.0	3.2	tooth	
GrA-50511	Southern Bight	1260	40	43.3	-20.3	12.7	8.8	4.0	bone	
GrM-10157	Wadden Sea, Texel	1225	20	45.4	-20.1	16.6	9.6	3.2	cranium	
GrM-10158	Wadden Sea, Texel	1205	20	45.5	-20.0	16.7	9.7	3.2	cranium	
GrM-12819	Wadden Sea, Texel	1212	15	43.3	-19.8	15.7	10.8	3.2	cranium	
GrA-31286	Zeeland, Westerschelde	1200	25	49.6	-19.5	17.1	12.0	3.4	bone	
GrA-65510	Zuid-Holland, Maasvlakte	1175	30	47.0	-20.6	16.0	10.8	3.4	cranium	
GrM-12519	Zeeland	1141	13	46.5	-20.0	17.0	12.3	3.2	vertebra	
GrM-10814	Zeeland	1115	12	42.5	-19.5	15.6	11.9	3.2	mandible	
GrM-12518	Zeeland	1035	14	47.5	-20.0	17.4	9.4	3.2	cranium	
GrA-66669	Zuid-Holland, Den Haag	1015	30	46.2	-19.7	16.7	10.9	3.2	vertebra	
GrM-12512	Zeeland	986	14	46.7	-19.9	17.2	10.6	3.2	mandible	
GrM-12513	Zeeland	975	13	45.8	-19.7	16.7	10.0	3.2	vertebra	
GrM-12594	Zeeland	951	13	46.4	-20.3	16.8	12.2	3.2	cranium	
GrM-10150	Wadden Sea, Texel	905	20	43.9	-18.0	16.0	13.6	3.2	humerus	
GrA-67125	Zuid-Holland, Den Haag	875	30	44.4	-19.1	16.1	11.3	3.2	humerus	
GrM-10156	Wadden Sea, Texel	840	20	43.8	-19.7	15.9	14.0	3.2	mandible	
GrM-10172	North Sea	791	17	40.5	-19.4	14.6	12.4	3.2	bone	
GrM-10162	Wadden Sea, Texel	730	20	43.0	-19.2	15.7	10.7	3.2	femur	
GrA-68787	Zuid-Holland, Monster	730	30	45.4	-19.4	16.6	12.5	3.2	mandible	
GrM-10163	Wadden Sea, Texel	695	20	43.5	-19.8	15.8	12.9	3.2	femur	
GrM-12511	Zeeland	654	13	46.7	-19.6	17.2	11.8	3.2	cranium	
GrM-10160	Wadden Sea, Texel	630	20	42.5	-20.0	15.4	12.7	3.2	cranium	
GrA-69069	Noord-Holland, Noordwijk	585	30	42.8	-18.3	15.5	14.6	3.2	scapula	
GrA-68049	North Sea	540	30	42.5	-19.9	15.4	11.5	3.2	mandible	
GrA-61784	Noord-Holland, Wijk aan Zee	485	35	43.4	-18.5	15.5	13.7	3.3	mandible	
GrM-12592	Wadden Sea, Griend	477	13	46.0	-17.2	16.8	15.2	3.2	pelvis	



lab code	locality	age BP	σ	C%	$\delta^{13}\text{C}$ (‰)	N%	$\delta^{15}\text{N}$ (‰)	C/N	skeletal element	remarks
GrA-62687	Zuid-Holland, Biesbosch	470	30	13.3	-19.9	4.5	13.5	3.5	cranium	
GrA-67126	Zuid-Holland, Den Haag	450	30	41.7	-18.9	15.1	13.4	3.2	femur	
GrM-11117	Wadden Sea	374	17	35.7	-20.1	13.0	12.2	3.2	tooth	
GrM-12514	Zeeland	356	13	47.9	-19.4	17.6	14.1	3.2	cranium	
GrA-66670	Zuid-Holland, Den Haag	355	30	47.3	-20.1	17.1	11.4	3.2	vertebra	
GrM-10351	Schiermonnikoog	340	15	43.8	-18.5	16.3	13.1	3.1	bone	
GrM12013	North Sea	338	11	45.9	-20.5	16.3	10.7	3.3	bone	
GrA-69720	Wadden Sea, Texel	335	35	41.9	-19.9	15.2	12.9	3.2	vertebra	
GrM-12590	Zeeland, Domburg	334	13	46.8	-18.5	17.1	11.6	3.2	femur	
GrM-10152	Wadden Sea, Texel	310	25	42.6	-21.6				femur	
GrA-69722	Wadden Sea, Texel	300	35	43.4	-20.1	15.9	13.6	3.2	vertebra	
GrA-37072	Eurogully	280	35	40.9	-18.2	13.5	12.2	3.5	humerus	
GrA-68584	Zeeland, Vlissingen	250	30	41.0	-19.5	14.8	13.5	3.2	cranium	
GrA-68309	North Sea	248	28	44.8	-19.9	16.2	12.3	3.2	mandible	
GrM-10159	Wadden Sea, Texel	235	20	46.2	-19.5	16.9	11.3	3.2	cranium	
GrA-64893	North Sea	225	30	44.1	-17.0	15.5	15.1	3.3	tibia	
GrA-67581	Zeeland, Oostkapelle	225	30	44.9	-18.0	16.3	11.2	3.2	cranium	
GrM-12348	Wadden Sea, Terschelling	223	14	45.6	-13.4	16.5	13.4	3.2	tibia	
GrM-10149	Wadden Sea, Texel	220	20	43.1	-18.4	15.5	12.8	3.2	humerus	
GrA-67523	Wadden Sea, Holwerd	210	30	46.9	-18.1	17.0	11.8	3.2	tibia	
GrM-10200	North Sea	207	13	45.3	-19.7	16.4	11.6	3.2	bone	
GrA-63668	North Sea	205	30	46.8	-17.2	17.3	11.1	3.2	bone	
GrA-64239	North Sea	200	30	47.0	-19.6	17.0	11.9	3.2	bone	
GrA-64895	North Sea	195	30	44.6	-19.2	15.1	11.3	3.5	tibia	
GrM-10173	North Sea	191	16	42.9	-19.2	15.5	13.4	3.2	bone	
GrA-68059	North Sea	191	30	39.8	-18.6	14.4	10.6	3.2	cranium	
GrA-68655	Zuid-Holland, Wassenaar	190	30	45.6	-17.7	16.7	12.1	3.2	vertebra	
GrM-10168	Wadden Sea, Texel	190	20	45.0	-17.8	16.3	11.8	3.2	femur	
GrM-12516	Zeeland	178	13	46.9	-18.5	17.2	12.1	3.2	fibula	
GrA-68310	North Sea	175	30	45.1	-19.5	16.3	11.8	3.2	mandible	
GrA-69018	Zeeland, Sluis	170	30	47.5	-19.5	17.0	12.6	3.3	humerus	
GrA-65315	Noord-Holland, Bergen aan Zee	165	30	41.6	-17.4	14.5	11.6	3.3	humerus	
GrA-69724	Wadden Sea, Texel	165	30	45.2	-19.3	16.6	10.9	3.2	femur	
GrA-69020	Zeeland, Sluis	160	30	43.8	-19.9	15.6	12.6	3.3	pelvis	
GrM-10151	Wadden Sea, Texel	160	20	45.3	-19.6	16.4	10.1	3.2	humerus	
GrM-10164	Wadden Sea, Texel	160	20	39.8	-19.9	14.6	12.6	3.2	femur	
GrM-12346	Wadden Sea, Schiermonnikoog	159	14	44.6	-19.2	16.1	13.6	3.2	tibia	
GrA-69723	Wadden Sea, Texel	155	35	45.1	-18.5	16.5	12.1	3.2	femur	
GrM-12589	Zeeland, Domburg	144	12	46.9	-19.3	17.2	11.8	3.2	mandible	
GrA-69019	Zeeland, Sluis	140	30	47.4	-19.6	17.0	12.6	3.3	cranium	
GrM-10199	North Sea	130	14	45.8	-20.0	16.7	11.6	3.2	bone	
GrA-64894	North Sea	120	30	40.8	-18.2	14.4	11.7	3.3	tibia	
GrA-64891	Wadden Sea	115	30	43.8	-19.9	15.7	11.2	3.2	cranium	
GrA-64892	Wadden Sea	75	30	45.3	-19.6	16.2	12.3	3.3	cranium	
GrA-69016	North Sea	0	25	48.8	-19.6	17.0	12.4	3.4	cranium	
GrA-69725	Zuid-Holland	0	25	44.2	-19.8	16.1	12.2	3.2	humerus	

